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Future makers or future takers? A scenario analysis of climate change and the Great Barrier Reef

Erin Bohensky [a,*], James R.A. Butler [b], Robert Costanza [c], Iris Bohnet [d], Aurélie Delisle [e], Katharina Fabricius [f], Margaret Gooch [g], Ida Kubiszewski [c], George Lukacs [h], Petina Pert [d], Eric Wolanski [f,h]

[a] CSIRO Ecosystem Sciences and Climate Adaptation Flagship, Private Mail Bag, Aitkenvale, QLD 4814, Australia
[b] CSIRO Ecosystem Sciences and Climate Adaptation Flagship, EcoSciences Precinct, GPO Box 2583, Brisbane, QLD 4001, Australia
[c] Institute for Sustainable Solutions, Portland State University, Portland, OR 97201, USA
[d] CSIRO Ecosystem Sciences and Water for a Healthy Country Flagship, Australian Tropical Forest Institute, James Cook University, PO Box 12139, Earlville BC, Cairns, QLD 4870, Australia
[e] School of Earth and Environmental Sciences and School of Business, James Cook University, Townsville, QLD 4811, Australia
[f] Australian Institute of Marine Science, PMB 3, Townsville MC, QLD 4810, Australia
[g] Great Barrier Reef Marine Park Authority, Townsville, QLD 4810, Australia
[h] Australian Centre for Tropical Freshwater Research, James Cook University, Townsville, QLD 4811, Australia

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ABSTRACT

The extent to which nations and regions can actively shape the future or must passively respond to global forces is a topic of relevance to current discourses on climate change. In Australia, climate change has been identified as the greatest threat to the ecological resilience of the Great Barrier Reef, but is exacerbated by regional and local pressures. We undertook a scenario analysis to explore how two key uncertainties may influence these threats and their impact on the Great Barrier Reef and adjacent catchments in 2100: whether (1) global development and (2) Australian development is defined and pursued primarily in terms of economic growth or broader concepts of human well-being and environmental sustainability, and in turn, how climate change is managed and mitigated. We compared the implications of four scenarios for marine and terrestrial ecosystem services and human well-being. The results suggest that while regional actions can partially offset global inaction on climate change until about mid-century, there are probable threshold levels for marine ecosystems, beyond which the Great Barrier Reef will become a fundamentally different system by 2100 if climate change is not curtailed. Management that can respond to pressures at both global and regional scales will be needed to maintain the full range of ecosystem services. Modest improvements in human well-being appear possible even while ecosystem services decline, but only where regional management is strong. The future of the region depends largely on whether national and regional decision-makers choose to be active future 'makers' or passive future 'takers' in responding to global drivers of change. We conclude by discussing potential avenues for using these scenarios further with the Great Barrier Reef region's stakeholders.

1. Introduction

In 1999, Australian futurist Doug Cocks described a divided world of future makers and takers. Australia, he argued, could either be a *future maker*, actively engaged in shaping all aspects of the future, or it could be a *future taker*, passively responding to what comes its way (Cocks, 1999). This choice is implicit in the current debate in Australia about action on climate change (Christoff, 2010), and begs a critical question: to what extent can proactive national, regional and local responses to climate change and other global drivers shape future outcomes, at least at these sub-global levels, when forces of global change are beyond national, regional or local control? The significance of scale in understanding and negotiating global environmental change has been emphasized in the literature (e.g., Wilbanks and Kates, 1999; Lebel, 2005), yet the challenges presented by these scale dynamics on the ground remain formidable.

The dichotomy of takers and makers has particular relevance to Australia's Great Barrier Reef (GBR), the world's largest coral reef ecosystem and an international, national and local icon that is threatened by change at multiple scales. In 2009, the Great Barrier Reef Marine Park Authority (GBRMPA) identified the following issues in order of priority as threatening the GBR's ecological resilience: climate change, continued declining water quality from

* Corresponding author. Tel.: +61 7 4753 8569; fax: +61 7 4753 8600.
E-mail address: erin.bohensky@csiro.au (E. Bohensky).

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catchment runoff, loss of coastal habitats from development and impacts from commercial and traditional fishing of threatened species (GBRMPA, 2009). Increasing sea surface temperatures due to global climate change have already led to regional-scale coral bleaching events on the GBR, and coral bleaching, coral mortality and biodiversity depletion are predicted to continue, possibly with increased frequency in coming decades (Preston and Jones, 2006; Hoegh-Guldberg et al., 2007). As in other marine ecosystems, these threats are interactive (Hughes et al., 2007). While the GBRMPA introduced a major rezoning policy in 1998 to address the impact of overharvesting on the ecological resilience of the GBR (Olsson et al., 2008), declining water quality from agricultural run-off may also reduce the resilience of corals to climate change impacts (Wooldridge, 2009; Wooldridge and Done, 2009).

The threats to the GBR outlined above need to be managed through a multiple-scale, cross-agency and cross-community approach, and the GBR itself needs to be conceptualized as a catchment-to-reef system. Currently, numerous agencies share responsibility for managing the GBR and catchment, but there is no unified institutional management arrangement for the region, an artefact of Australia's historical division of federal and state powers. Arguably, the institutional arrangements for the region have resulted in mismatches between governance and ecosystem processes, exemplified by management that has been largely sectoral, narrowly focused and short-term (Ferrier, 2007). Although there is great concern among GBR institutions about future uncertainty, and recognition of the need for longer-term planning (GBRMPA, 1994, 2009; Johnson and Marshall, 2007), ongoing and integrated strategic planning by these institutions has been limited.

Scenarios—alternative future visions—provide a mechanism for individual and collective consideration and articulation of perceptions and aspirations for the future, and the opportunities and risks that may be associated with particular decisions. Scenarios have been widely used elsewhere to illuminate the enabling conditions for and constraints on current and future management approaches and strategies (MA, 2005), identify possible adaptations and ultimately assist agencies to move from a position of 'taking' to 'making' desirable future change.

Scenario exercises have been conducted in the GBR region at a range of scales and for various purposes (Roebeling et al., 2005; Bohnet and Smith, 2007; Bohnet, 2008; Bohnet et al., 2008), and have contributed to an understanding of the implications of potential future change by a wide range of local and regional stakeholders. Yet to date, no comprehensive future analysis of the GBR region exists that is based on the downscaling of available global climate change projections and other aspects of global change, to enable exploration of how global change may influence and interact with regional and local responses.

To begin working toward such an exploration of the GBR's future, we seized a window of opportunity to conduct a scenario exercise that synthesized existing information to examine how key drivers of global climate change and its mitigation at the GBR scale might impact on ecosystem services and human well-being. In this paper we discuss the process and results of this exercise, implications for management and potential avenues for using these scenarios further with GBR stakeholders.

2. Methods

2.1. Study site

The Great Barrier Reef (Fig. 1.) spans 2300 km of Australia's northeast coast, and covers an area of approximately 348,000 km^2. Supporting a diversity of marine life, it has been protected as a Marine Park since 1975 and as a World Heritage Area since 1981.

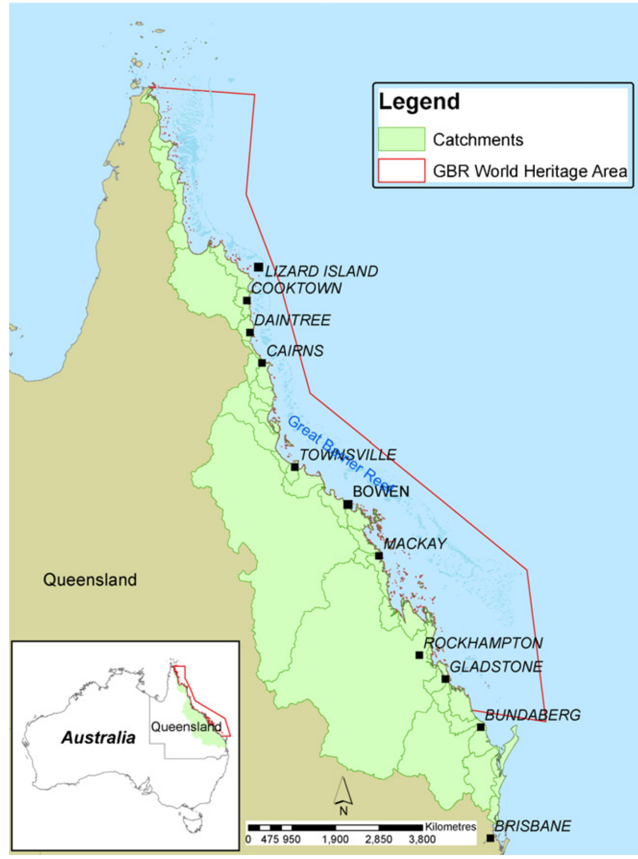

Fig. 1. Location of the Great Barrier Reef region.

The contribution of the GBR to the Australian economy was estimated to be AUD5.4 billion p.a. in 2006–2007 (Access Economics, 2008), or 4.7% to Australia's Gross Domestic Product (GDP) in 2007–2008 (Oxford Economics, 2009). This consisted mostly of tourism (AUD6 billion p.a.), followed by recreational (AUD623 million p.a.) and commercial fishing (AUD251 million p.a.), which together employ approximately 66,000 people. Shipping activity through the GBR is a vital link in the production chain for many industries and services in regional centres. The GBR has high cultural value for Indigenous Australians, internationally important iconic and scientific value (GBRMPA, 2009) and is part of the Australian national identity (Young and Temperton, 2008).

The adjacent catchment area (426,000 km^2), covering about 22% of the state of Queensland, supports some of the most diverse landscapes on the Australian continent, including the tropical rainforests of the Wet Tropics World Heritage Area, drier tropical and subtropical savannahs, mountain ranges and coastal plains. The main land uses include cattle grazing (about 75% of the catchment area), natural forests, production forestry, intensive agriculture, cropping, sugarcane cultivation, horticulture, mining and urban areas. The current population of the catchments is approximately 1.12 million and is expected to grow to 1.58 by 2026 (OESR, 2008), fuelled largely by mining and industrial activity.

Management of the GBR and its catchment area is shared by the Australian and Queensland State Governments, and consequently is complex. The federal government has statutory powers to manage the GBR Marine Park through the GBRMPA, and the state government has responsibility for the in-shore GBR Coast Marine Park. To promote coordination in marine GBR management, intergovernmental co-management agreements have been established (Olsson et al., 2008). The GBR catchment is primarily under the aegis of the state government, who has responsibility for water quality regulation, land use planning, permitting and enforcement. The federal government also funds seven regional non-statutory Natural Resource Management (NRM) Boards which facilitate community-based land stewardship initiatives. Since 2003, catchment-derived water quality problems have been addressed by the Reef Water Quality Protection Plan (Reef Plan) (Australian Government and Queensland Government, 2003) and Reef Rescue (Australian Labour Party, 2007). The GBRMPA has primary responsibility for responding to climate change affecting the marine park. There are multiple local primary stakeholder groups who depend on the ecosystem services provided by the GBR and its catchments, including the tourism, commercial and recreational fisheries sectors, as well as agriculture. Secondary stakeholders include community, local councils, non-government organisations and service providers, and the Australian and global public (Butler et al., 2010). Many of the local stakeholders have established representative bodies who engage with federal and state government and NRM Boards at the local to regional scale through planning processes and forums.

2.2. Scenario analysis

'Scenario' is a term with multiple meanings. Scenario exercises vary in their purpose and hence their approach (Biggs et al., 2007). In this paper, we define scenario analysis as a structured process of generating imaginative future possibilities which have implications for ecosystems and human well-being. Scenarios consist of narratives that consider how alternative futures, typically related to a particular focal issue (O'Brien, 2000), may unfold from combinations of highly influential and uncertain drivers, and their interaction with more certain driving forces. In fact, the very advantage of scenarios as a futures analysis method lies in both the process and outputs of a systematic examination of how uncertainties and trends interact (Schoemaker, 1991).

Scenarios should not be mistaken for predictive models, although the two can complement each other (Coreau et al., 2009). Scenarios differ from forecasts and predictions in that they explore the range of future uncertainty (Schoemaker, 1991) and enable their users to formulate complex sets of hypotheses about the future rather than to predict specific outcomes (Coreau et al., 2009). Unlike predictions, notes Slaughter (2002), scenarios recognize humans as agents and makers of history. Although aspects of the future worlds depicted by scenarios may come to eventuate, scenarios are often best viewed as stylized versions of reality from which we can learn.

Scenarios are best suited to exploring situations where uncertainty is high and controllability is low (Peterson et al., 2003). For example, climate change and global governance are largely beyond the control of a region such as the GBR. In these situations, scenarios can help to illuminate the consequences of these global drivers of change and to formulate robust local responses. Importantly, scenarios can help to reveal key branching points in the future (Gallopín, 2002), and policy and value changes that may be required to achieve a particular future outcome. Thus, scenarios can be crucial in transition processes (Wiek et al., 2006).

For several decades, scenarios have been developed for a range of applications from global to local scales, including corporate strategy (Wack, 1985), political transition (Kahane, 1992), and community-based natural resource management (Wollenberg et al., 2000; Evans et al., 2006). A recent literature review (Varum and Melo, 2010) shows that scenarios are experiencing a resurgence of popularity, including for applications such as nanotechnology (Wiek et al., 2009) which involve numerous 'known unknowns'. Despite this, a long list of methodological challenges to the construction of scenarios remains, particularly for their qualitative components. These include ensuring plausibility and consistency of scenarios (Tietje, 2005), which are problematic concepts when dealing with the elusive, ever-changing future that is inherently viewed from different perspectives (Bohensky et al., 2011). Other challenges include determining whether and how probabilities should be assigned to scenarios so that uncertainty can be communicated to decision-makers (Tonn, 2005; Groves and Lempert, 2007), and bounding scenario space to define the relative influence of internal and external dynamics (Fink et al., 2005). Slaughter (2002) notes the problem of "free-floating" when scenarios are developed without invoking a conceptual framework of how the world works. One of the greatest obstacles to the application of scenarios to real-world problems seems to lie in the confusion caused by an extremely broad range of scenario definitions and characterizations (Godet, 2000), although several studies have attempted to illuminate and organize the major schools of thought (Biggs et al., 2007; Varum and Melo, 2010). With this in mind, the GBR scenarios exercise was intended in part to help raise awareness and dispel confusion about scenarios among GBR decision-makers.

2.3. Development of GBR scenarios

Scenarios were developed by a team of local and international biophysical and social scientists from research and government institutions (the authors of this paper) to better understand key uncertainties about the future, and potential trade-offs in the quantity, quality and flows of ecosystem services, and implications for human well-being. We used the Millennium Ecosystem Assessment conceptual framework as our basis for analysis (Fig. 2a), and for developing exploratory scenarios that sketched out four plausible future worlds (MA, 2005). The opportunity to develop scenarios for the GBR region emerged during a two-week workshop in October 2009 to discuss an approach for identifying, valuing and managing ecosystem services in the GBR and adjacent catchments. It became apparent that several data sets, analyses and models were available to undertake a rapid scenario-planning exercise during the workshop. Because of the presence of key stakeholders from the GBRMPA and the Queensland Government, the scenarios could serve to inform ongoing policy processes and provide a springboard for longer-term collaborative futures analysis.

We began by reviewing previous futures studies at global, national and regional (e.g., GBR) scales, representing several decades' worth of research on drivers and trends (see Appendices A and B for examples). This included the national-scale work of Cocks (1999), the Business Council of Australia (2004), and Cork and Delaney (2005), as well as previous scenarios for the GBR. To form a conceptual model of drivers in the GBR, we drew heavily on the work of Bohnet et al. (2008) which involved interviews with 47 leaders in academia, business and government about key drivers of change and their dynamics for the region. Drivers identified in this study were categorized into three interdependent clusters, whose relationships continuously evolve (Petschel-Held et al., 2006): regional leadership, impacts of climate change, and Australia's engagement with global society (Fig. 2b).

Based on the findings of these analyses, and the GBRMPA's concerns about climate change impacts on the GBR, the scenarios were developed around the drivers of climate change at the global scale and of mitigation of climate change at national, regional and local scales. Because we wanted to undertake a holistic integrated analysis of driving forces of climate change at all relevant scales, we focused on the underlying worldviews and values related to societal development. Thus scenarios focused on this source of uncertainty rather than climate change projections themselves.

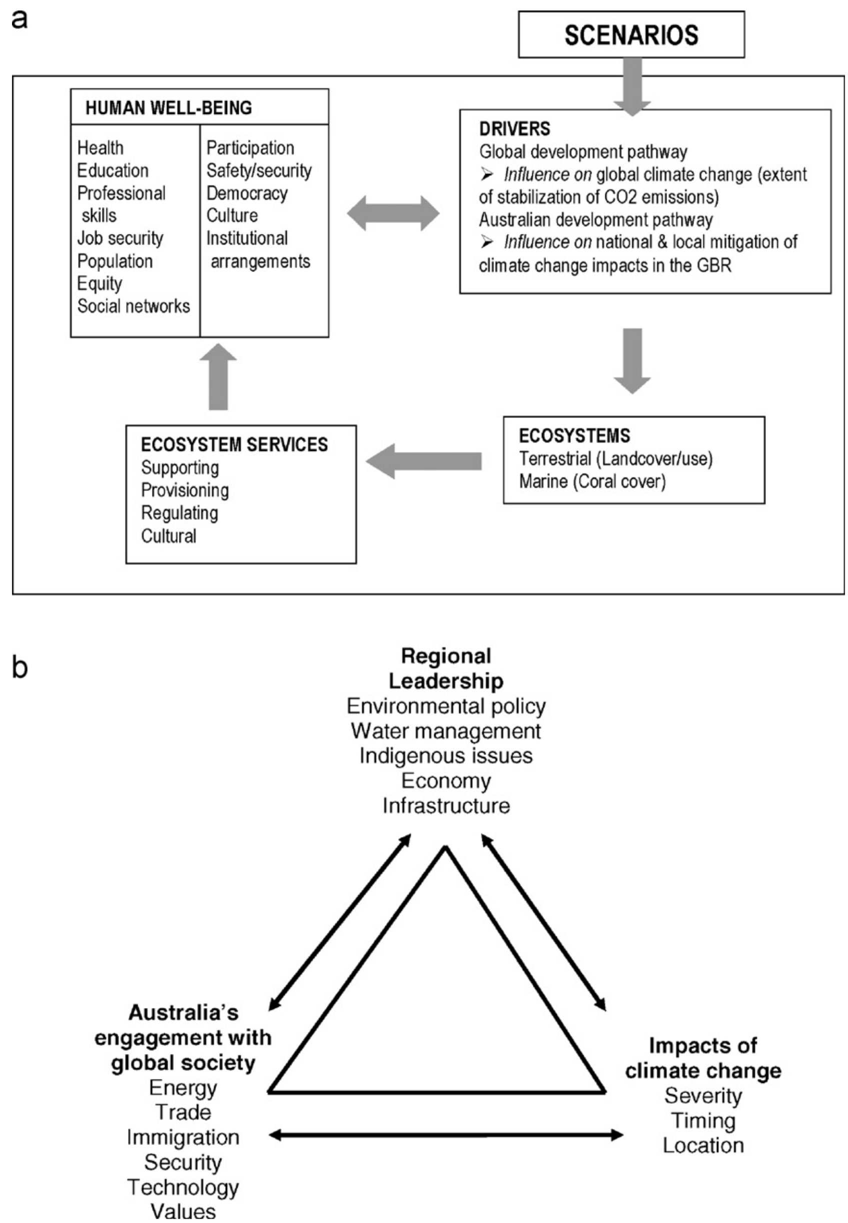

Fig. 2. (a) Conceptual framework for analysis. Scenarios were used to explore two key drivers of change: the global development pathway, which influences global climate change, and the Australian development pathway, which influences climate mitigation at the Great Barrier Reef (GBR) scale, and how these might impact on terrestrial and marine ecosystems in the GBR, four broad types of ecosystem services and selected indicators of human well-being (adapted from MA, 2005). (b) Conceptual model of key drivers in the GBR region and their relationships (adapted from Bohnet et al., 2008). Individual drivers were identified in 47 interviews and organized into three clusters of similar drivers: regional leadership, impacts of climate change, and Australia's engagement with global society. Relationships between these clusters are continuously changing, but in general, the type of regional leadership in the GBR mitigates Australia's engagement with global society as well as impacts of climate change. Impacts of climate change *can* influence regional leadership and engagement with global society (e.g., on climate and energy policy). Australia's engagement with global society can influence the type of regional leadership in the GBR.

We also established that while some of the previous GBR scenarios have focused at least partly on climate change, these were not completely aligned with our objectives. Hoegh-Guldberg and Hoegh-Guldberg (2008) considered climate change projections for the GBR World Heritage Area and selected industries only, and without developing narratives that explored implications and feedbacks. Bohnet et al. (2008) constructed narratives of climate change in combination with governance, and focused on the catchment and reef, but these were not adequately specific in their definition of climate events or global economic drivers.

We followed the commonly used scenario-axes method in which four scenarios were developed around two axes of uncertainty (Wack, 1985; MA, 2005; Groves and Lempert, 2007). We chose the year 2100 as the endpoint for our scenarios to explore societal responses to climate change over a longer period, and to retain consistency with the timeline of projections in the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report.

2.3.1. Axis 1: Empty World/Full World: Globe

Our first axis depicts two pathways for global development. One, the mainstream model of development, is based on a number of assumptions created during a period when the world was still relatively empty of humans and their built infrastructure. In this "empty world" context, built capital was the limiting factor, while natural, human and social capital were often abundant (Costanza, 2008). During this period, environmental and social "externalities" were assumed to be relatively small and irrelevant, the economy was seen to consist of only marketed goods and services and it was desirable to increase production and consumption of these. While the logic of this model may be diminishing amid a growing global discourse on sustainable development and natural resource constraints that are being experienced by many regions worldwide, the return of the "empty world" mindset is not unfathomable, given shifts in the demographic, political and economic balance of power, as evident in a range of global scenarios such as the Millennium Ecosystem Assessment's *Order from Strength* (MA, 2005) or Shell's *Scramble* (Shell, 2008).

The second pathway is that of the dramatically different "full world," now dominated by humans and their built environment. An alternative model of development reconceptualizes the nature and purpose of the economy, with its primary goal to sustainably improve human well-being and quality of life. Material consumption is merely means to that end, not an end in itself. Material consumption in excess of basic needs can actually reduce physical and psychological well-being, while natural, human and social capital are now the limiting factors to sustainable human well-being in many countries.

These two development pathways yield two options for global climate change. The first option follows the IPCC's SRES A1 scenario storyline (Nakicenovic and Swart, 2000), which describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. In this scenario, CO_2 is projected to reach 850 ppm and mean surface air temperatures to increase by at least 3 °C by 2100 (IPCC, 2007). Although there is uncertainty associated with these projections, they are based on the best available understanding, and as such are the best present estimates of global climate change impacts on the GBR. We did not consider the IPCC's intervention scenarios (i.e., those that include climate policies) (Girod et al., 2009) which were not part of the IPCC (2007) report.

The second option is that an international climate agreement enables CO_2 levels to return to 350 ppm, representing a 50–80% reduction in 1990 levels, and temperatures to not increase by more than 2 °C, by 2100. This is the widely supported target for CO_2 as the upper limit considered necessary for sustaining a planet "similar to the one on which civilization developed and to which life on earth is adapted" (Hansen et al., 2008).

2.3.2. Axis 2: Empty World/Full World: Australia

Our second axis reflects the degree to which Australia's pathway of development follows the "empty world" or the "full world", and influences how regional and local pressures on the GBR are mitigated.

Australia may or may not conform to the given global development pathway. Throughout its history, Australia has displayed a unique brand of independence due in part to its geographic isolation, now being rapidly overcome by the close links it is forging with a global economy, politics and culture (James, 2007; Stevenson, 2007). Australia's future very much depends on how it defines, and sustains, itself as a nation in a relatively remote but highly diverse, rapidly changing corner of the world (Gray and Lawrence, 2001; Cork and Delaney, 2005).

Resource management in Australia has been historically dominated by the belief that 'economic development is a good thing' (Cocks, 1999), but some longstanding traditions, such as agricultural land use, are dissolving due to changing perceptions as well as global contexts (Dunlop et al., 2002; Christoff, 2010). Australia may continue on its historical trajectory or it can move toward broader concepts of welfare that include ecosystem services and human well-being. While the idea that alternative measures are needed to measure well-being is gaining ground globally (MA, 2003) and in some nations (Landcare Research Scenarios Working Group, 2007), in Australia and the GBR, a tension between the 'full world' and 'empty world' mindsets remains evident. While such a choice lies mainly in the hands of national government, there is room for regional decision-makers to influence this choice on the basis that the GBR is an irreplaceable national as well as global asset.

2.3.3. Combining two uncertainties

Four scenarios were developed and named as follows (Fig. 3): (1) *Trashing the Commons*: Both the world and Australia follow an Empty World path, and climate emissions reach 850 ppm by 2100, (2) *Treading Water*: The world follows an Empty World path, and climate emissions reach 850 ppm by 2100, but Australia follows a Full World path, (3) *Free Riders*: The world follows a Full World path, and climate emissions reduce to 350 ppm by 2100, but Australia follows an Empty World path, and (4) *Best of Both Worlds*: Both the world and Australia follow a Full World path, and climate emissions reduce to 350 ppm by 2100.

2.3.4. Ensuring consistency and credibility

To ensure consistency and credibility of the scenario narratives, we checked for internal inconsistencies in each scenario by re-reading the narrative text and having the scenarios independently

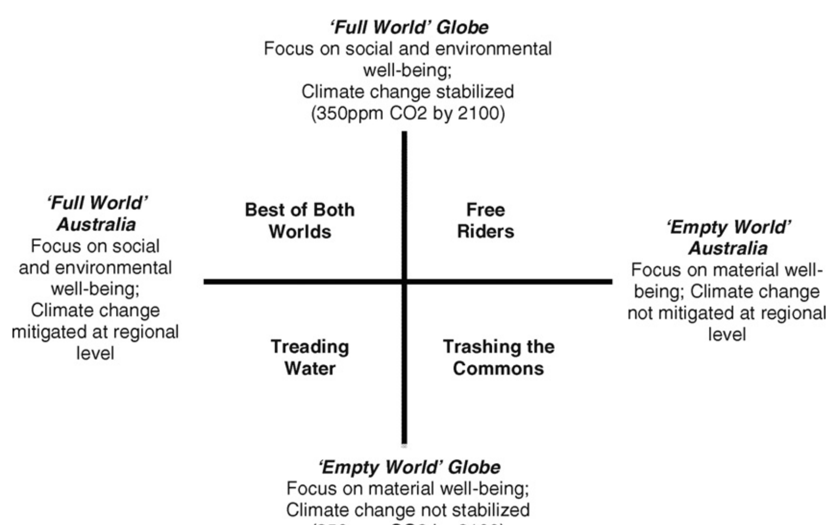

Fig. 3. Four scenarios were developed from combinations of alternative development pathways for the world and for Australia.

reviewed by non-participating colleagues that were familiar with the GBR. We also presented these scenarios to the GBRMPA and at an international climate change conference. It was observed by a GBRMPA staff member, for example, that the two scenario axes are not independent, as Australian policy is frequently overshadowed by the global impact of Australian industrial activity, and would therefore affect coal exportation, for example. All perceived inconsistencies were noted and addressed in a revised version of the scenarios. More formal methods for dealing with inconsistency (e.g., Tietje, 2005) were not employed at this stage in the scenario development, but could be in a longer-term comprehensive scenario project.

2.4. Implications for marine and terrestrial ecosystems

To assess the outcomes of the scenarios for marine and terrestrial ecosystems, we modelled future coral cover and land cover/use.

2.4.1. Coral cover

Coral cover was estimated to the year 2100 using the HOME ecohydrology model (Wolanski et al., 2004; Wolanski and De'ath, 2005). The model represents the average coral cover of 261 reefs in the GBR between Bowen and Lizard Island, with the ecology determined by herbivorous fish, algae, corals and crown-of-thorns starfish (COTS) (*Acanthaster planci*), a coral predator which can form very large numbers, leading to outbreaks. The ecosystem is forced by (1) riverine fine sediment, (2) nutrients and turbidity increasing as a result of land use and transient river floods, (3) occasional tropical cyclones, and (4) bleaching events in summer from climate change (warming and ocean acidification). The model parameters that vary under the four scenarios are given in Table 1.

We note several caveats in interpreting the HOME model which may make these predictions optimistic; namely:

(1) The model does not include ocean acidification. Although it has slowed coral growth (De'ath et al., 2009), ignoring acidification may be justified in scenarios in which CO_2 stays at 350 ppm.
(2) It assumes that rainfall and the frequency and intensity of floods and cyclones will in the future remain the same as in the period 1969–2002 (for which there are data). Coral cover could be less than predicted if flood or cyclone frequency and/or intensity increases.
(3) It assumes no change in the future in the wind field during coral mass spawning (i.e. the 1969–2002 variability remains unchanged); this controls the connectivity between reefs and the resilience of coral reefs. Data are unavailable to test this hypothesis.
(4) In the model the coral death rate from bleaching is that experienced in the two GBR coral mass bleaching events during the last 10 years. This mortality was much less than that in other places such as the Seychelles in the 1998 global coral bleaching event.

Table 1
Values of parameters used in HOME model (only parameters that varied under the four scenarios are included).

Scenario	Riverine fine sediment and nutrients	Bleaching events frequency
Trashing the Commons	2 × present value	2 × present value
Free Riders	2 × present value	Present value
Treading Water	0.5 × present value	2 × present value
Best of Both Worlds	0.5 × present value	Present value

(5) Each reef is given the same weight when calculating the average.

2.4.2. Land cover/use

A base map was developed for the GBR catchment from a series of data sets (QEPA, 2005; QDNRW, 2006a,b; Witte et al., 2006). To reduce complexity in the map, related land covers and uses were combined; the resulting base map for the GBR catchment contains 14 categories, which were appended to a map of coral cover (Fig. 4). Land use and remnant vegetation cover as at 2003 in the GBR catchment was mapped to provide the baseline for developing projections for the GBR catchment in 2100. Local knowledge of the GBR catchment among the scenario development team informed the development of the land cover projections, as an analysis based on time-series data for terrestrial ecosystems was beyond the scope of this exercise. Simple deterministic rules and assumptions for converting natural areas and agricultural land to more intensive uses were developed within the group and through expert opinion, and were based on a standard schematic of land cover change used in the Millennium Ecosystem Assessment (DeFries et al., 2004; Rodríguez et al., 2006). The land cover/use classes were grouped into four categories (cover types) which included: natural terrestrial ecosystems, coastal ecosystems, marine ecosystems and agricultural/urban areas.

Marine and terrestrial ecosystems, as measured by coral cover and land cover/use, respectively, were compared under these four scenarios, by interpreting the models and through expert opinion during the workshop.

2.5. Outcomes for ecosystem services and human well-being

Ecosystem services provided by marine and terrestrial ecosystems were categorized as: (1) provisioning services, or tangible benefits obtained from ecosystems such as water, food, timber, and minerals; (2) regulating services that regulate ecosystem processes such as climate, water quality, and air; (3) supporting services, which include processes such as soil formation, photosynthesis, and nutrient cycling; and (4) cultural services that provide recreational, aesthetic, or spiritual benefits (MA, 2003).

Human well-being indicators included health, education, professional skills, job security, population, equity, participation, security/safety, democracy, social networks, culture and institutional arrangements. Health includes access to clean air and water, sufficient nutritious food, feeling well, access to health care facilities, work/life balance and mental health (MA, 2003). We also considered health issues that result from increasing global temperatures, such as mosquito-borne diseases, which could become more widespread in the region (Bryan et al., 1996). However, due to time constraints, we did not consider a whole range of potential health problems associated with climate change including human responses to increased daily temperatures (McMichael et al., 2006).

Education was measured by the quality and interest in general education at all levels. We included professional skills as a separate indicator, using the rationale that in some scenarios, general education would be less valued than professional skills developed in the work place which would result in higher personal income, and possibly greater job security. Job security implies that workers are shielded from fluctuating labour markets and compensated for geographic mobility, training and other costs associated with employment (Allard, 2005). Population is another important indicator as population is expected to drive each of the other human well-being indicators; in this analysis we focused only on numbers, not structure. Furthermore, population projections for the GBR region are not readily available beyond 2050 (OESR, 2008). The effect of climate change might lead to an influx of climate

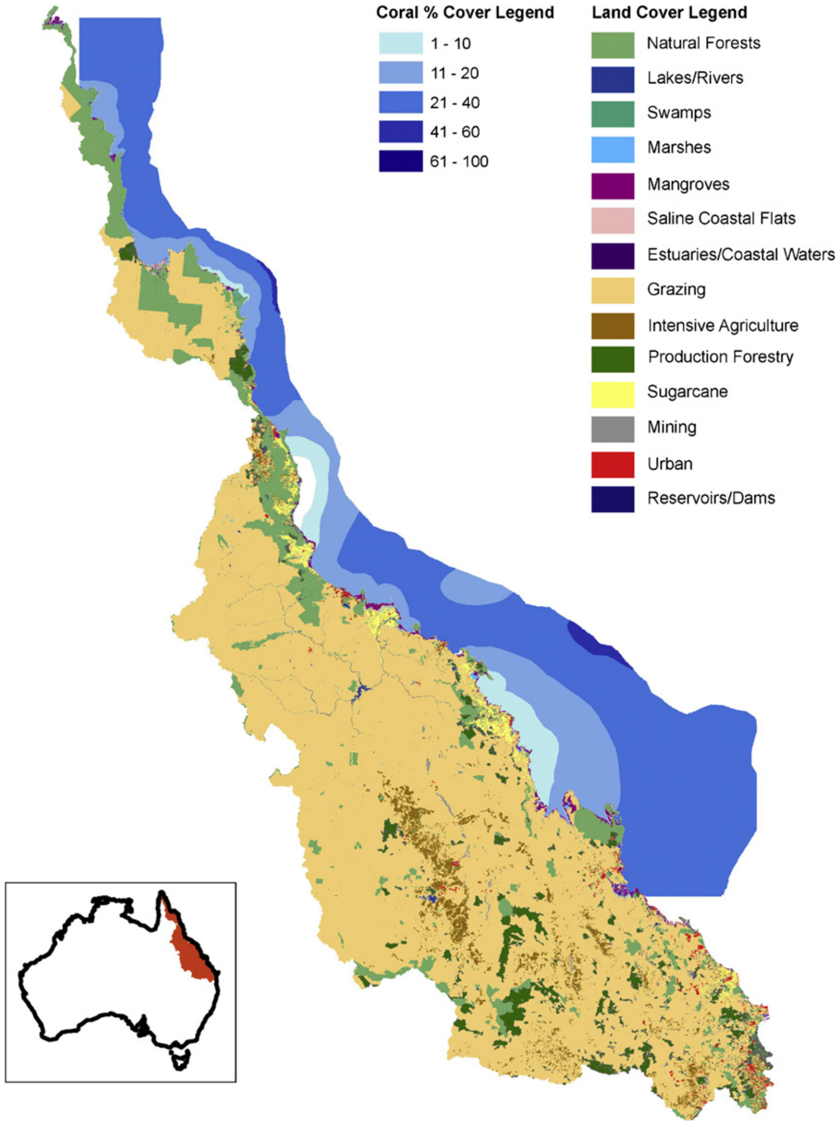

Fig. 4. Land cover/use in the GBR catchment and coral cover.
Land cover/use data are from QEPA (2005), QDNRW (2006a,b), and Witte et al. (2006).

change refugees (Garnaut, 2008). However, even estimating numbers of refugees is a complex task as we need to account for both the capacity of people to move and the legal frameworks of potential host countries (Garnaut, 2008).

Equity, meaning the fair distribution of rewards and resources (Leventhal, 1980) would vary in each scenario according to prevailing local and global commitments to social justice. We largely equated participation with rates of volunteerism (Putnam, 2000). Networks and social ties are essential components of social capital, generated when individuals cooperate for mutual benefit (Putnam, 1993). Networks would comprise both communities of interest (including online communities) as well as communities of place. Culture was identified as an indicator to represent expressions and celebrations of cultural diversity including Indigenous culture. The culture indicator also encapsulates a person's sense of belonging and identity.

Security is a key driver for decision-making related to climate refugees in the GBR region. This indicator is important on two levels: firstly in terms of personal and group tensions among different refugees and local residents and secondly the impact of erratic weather patterns on human safety and well-being. Finally, we included institutions to envision the impact of various institutional arrangements for each scenario.

Built environment indicators were also considered part of human well-being and included infrastructure, equipment and technological improvements (Nelson et al., 2007). We divided the built environment into quantity and quality measures. Our indicator for quantity included infrastructure and equipment required in each scenario, taking into consideration population pressures due to climate refugees and likely prevailing population policies. The indicator for quality assessed the properties of this built environment in terms of ecological footprint and methods of resource extraction (either extractive or more restorative methods). We also considered the quality of new technology in terms of its ecological footprint.

Using expert opinion among workshop participants to interpret the coral cover and land cover model results, qualitative changes in the conditions of the services provided by terrestrial and marine ecosystems, and in the selected indicators of human well-being, were projected in the four scenarios. Our analysis followed the methods of other Millennium Ecosystem Assessment studies (e.g., van Jaarsveld et al., 2005; Bohensky et al., 2006; Rodríguez et al., 2006). Each category of ecosystem service and component of human well-being was given equal weight, as we lacked appropriate information, such as stakeholder rankings of importance, that could allow weights to be assigned.

We chose not to assign probabilities or confidence levels to the outcomes of our analysis, for two main reasons: first, we did not want to mislead stakeholders into believing that some outcomes of the scenarios were more certain than others, and second, making meaningful probability estimates is extremely difficult given the complex dynamics of the drivers we investigated (Groves and Lempert, 2007).

3. Results

3.1. Scenario narratives and characteristics

From the development of the two axes, we developed narratives that described how each of the four scenarios would unfold (Table 2). Key scenario characteristics are presented in summary form in Table 3. Outcomes of the scenarios for supporting, provisioning, regulating and cultural ecosystem services provided by terrestrial and marine ecosystems in the four scenarios are summarized in Table 4.

3.2. Implications for marine and terrestrial ecosystems

3.2.1. Coral cover projections

The time-series plot of the predicted average coral cover on 261 reefs between Bowen and Lizard Island for the four scenarios is shown in Fig. 5. The scenarios depict four options for coral cover in the GBR by 2100:

(1) If global climate change is managed and mitigated through regional-scale catchment management, coral cover will be similar in 2100 to what it is now (*Best of Both Worlds*);
(2) If global climate change is not managed, but mitigated at a regional scale, there will be a very minimal level of coral cover (*Treading Water*);
(3) If global climate change is managed but not mitigated at a regional scale, there will be an intermediate level of coral cover (*Free Riders*);

Table 2
Scenario narratives.

Trashing the Commons	Free Riders
Australia and the rest of the world continue to pursue the ‘empty-world’ development pathway, focused on increasing economic growth. By 2100 global warming has exceeded 3.5 °C, sea level has risen by 1 m, cyclones have increased in intensity, marine waters are less alkaline (pH 7.7) and rainfall in GBR catchments has become more erratic. The population of the GBR catchment has reached 3 million, a result of agricultural and mineral industry expansion and intensification, urban growth and climate refugees from both southern Australia and the Asia-Pacific region. Global and national demand for food and minerals remains high, fuelling economic growth based on expanded irrigation and extractive industries, and is serviced by increased but poorly designed infrastructure.	Global action on carbon emissions and transition to a ‘full-world’ economic model averts a climate change catastrophe. After having reached maximum levels of 420 ppm at 2050, atmospheric CO_2 concentrations are stabilized at 350 ppm by 2100. In the GBR region climate change impacts have intensified up to 2050, but temperatures have stabilized at a $<2\,^{\circ}C$ increase by 2100. Seawater pH, storm intensity and rainfall patterns do not change drastically, and sea levels do not rise more than 0.3 m. However, Australia’s ‘empty-world’ mindset and *modus operandi* persists and it maintains an isolationist foreign policy and a social paradigm based on irrigated agriculture and extractive, market-based economic growth. Human population in the GBR catchments has increased to 2.5 million, mainly from intrinsic population growth and southern Australian migrants seeking lifestyle changes. Agricultural and some mining expansion have occurred, but are limited by more discerning export markets and international sanctions on environmentally unfriendly Australian products, which drives diversification and development of technology.
Corals have largely disappeared, and reefs have become algae-dominated. Pollution, overfishing and a lack of corals for shelter reduce fish biomass and diversity by 80% of 2010 levels. Coasts and islands have receded due to sea level rise, and swamps and marshlands have been polluted or reclaimed to accommodate the growing population. Terrestrial biodiversity also declines substantially, with biodiversity extinctions in the Wet Tropics, tree loss across the savannah from land clearing and drought, and the proliferation of invasive species. Clearing of native vegetation including mangroves, though previously prohibited, has resumed. Increasing demand for freshwater has drawn down the groundwater, requiring increased dam building and water transfers, resulting in reduced natural flow regimes. Desalinization plants increase. Grazing and production forests suffer from erratic rainfall patterns resulting in more frequent and intense droughts and floods.	Supporting and regulating ecosystem services in particular are under pressure. The condition of marine and terrestrial ecosystem services has declined due to centralized and ineffective management of agriculture, fisheries, aquaculture and urbanization, and terrestrial biodiversity is threatened by expansion and intensification of urban and agricultural areas, as well as invasive species. Terrestrial runoff of nutrients and sediments and over-exploitation of fishes are the main impacts on the reef, with coral cover declining to 20% by 2050, and fish biomass declining by 70%. Increasing demand for water and drawdown of groundwater requires construction of dams and desalinization plants.
By 2100, extractive use of ecosystems takes a massive toll on supporting, regulating and cultural ecosystem services, and the condition of provisioning services also declines, even though quantities produced of food, water supplies, minerals and farmed fish are at an all-time high. The international tourism industry shifts from biodiversity to beaches, casinos, theme parks and shopping worlds. High-impact aquaculture becomes the primary marine use. Shipping activity through GBR waters has trebled with new ports, mines and export markets for eagerly sought Queensland coal. Concern about ecosystem health has reduced as political agendas and media attention target other issues. This, in combination with population pressure, a focus on irrigation for agricultural outputs and erratic rainfall, results in severe decline in the quality and quantity of freshwater and marine water quality. With top-down plutocratic governance and dominance of multi-national companies, income disparity has increased and participation in tertiary education has declined. Sea level rise, storm intensification and high ambient temperatures in coastal towns have required massive urban and infrastructure re-design and retro-fitting at high cost to taxpayers. High costs of living combined with increased health and security risks reduce overall human well-being. Institutions are reactive, as the social consequences of ecological decline, and benefits of reversing it, are not readily perceived. Consequently the algal-dominated reef ecosystem is unlikely to return to its previous state even if restoration efforts are undertaken.	Infrastructure increases but is poorly designed and inefficient. Social inequity is evident and participation in formal education is low as young people leave school to join the workforce in mining and primary industries. Lack of community-based governance, strong business elites and income disparity combine to reduce overall human well-being. Planning and institutions are reactive and are not well-equipped to detect and respond to ecological problems.

Treading Water	Best of Both Worlds
There is no global action on climate change, and by 2100 global temperatures have warmed by more than 3.5 °C, sea level has risen by 1 m and seawater reduced to a pH of 7.7. In the GBR region, storm and cyclone intensities have increased, and rainfall has become more erratic. The human population in the GBR catchments exceeds 3 million, and is increasingly urban, fuelled by immigration in response to expanding opportunities from agricultural expansion and intensification and mineral industry intensification, and climate refugees from southern Australia and the Asia-Pacific region. Through strong, inspired leadership, Australia has made a transition to a 'full-world' economic model based on internalization of externalities and an emphasis on social equity and public participation in political decision-making. Impacts and local anthropogenic pressures on ecosystem services in the catchments are partially mitigated by pro-active, community-based governance. By 2050, coral cover is less than 20% due to annual bleaching, and reefs become algae-dominated, resulting in declining fish biomass and diversity. By 2100, coral cover is approaching 5% due to warming and ocean acidification. The constrained international tourism industry adapts by shifting away from reefs, and specializing on more intact areas and species (e.g. whale-watching), and tourism generally reduces its ecological footprint.	Global action on carbon emissions and global transition to a 'full-world' economic model averts a climate change catastrophe, with atmospheric CO_2 concentrations returning to 350 ppm by 2100. In the GBR region climate change impacts have intensified up to 2050, but temperatures have stabilized at 2 °C above pre-industrial levels by 2100. Sea level has risen by only 0.3 m. Australia also succeeds in introducing an economic model based on institutions for the commons, including mechanisms for internalizing externalities, an emphasis on social equity and global fair trade. In the GBR intrinsic growth and domestic immigration increases the population to 2 million.
In terrestrial and marine ecosystems, supporting, regulating and cultural ecosystem services are hard hit, with biodiversity extinctions in the Wet Tropics, tree death across the savannah and increasing invasive species. Commercial and recreational fisheries decline, but careful management prevents the complete collapse of stocks. Water quality declines with the intensification of grazing and agricultural systems to supply the large human population, and more erratic rainfall. This leads to a demand for more irrigation, requiring increased dam building and water transfers, but there is local resistance to loss of native vegetation and impacts on water courses are locally managed. Pro-active planning mitigates the impacts of sea level rise, storm intensification and high ambient temperatures on coastal towns, but marshlands and many of the coral cays and islands become inundated.	The condition of the reef continues to decline until mid-century due to high CO_2 levels and water quality decline in the early 2000s, before recovering by 2100 to 25% coral cover and higher fish diversity and biomass. The international reef tourism industry declines by mid-century but recovers and remains the primary regional industry, followed by low-impact agriculture and aquaculture and renewable energy aided by technological advances. Land use strives to achieve greater productivity from multi-service landscapes that include increased food production from rainfed agriculture and the incorporation of biodiversity and agriculture in agro-ecosystems. Terrestrial protected areas increase, and mining and broadacre grazing decline in favor of well-managed, locally confined systems.
Improved health and education, strong civil society and more even income distribution increases well-being, but this is tempered by high costs of living and conflict in Asia-Pacific, requiring strong border security. Planning processes and institutions are democratic and adaptive, with emphasis on increased learning about ecosystems and how they are linked to human well-being, but they are better able to respond to local than to global pressures.	Ecosystem services begin to rebound. Commercial fisheries are sustainably managed, and recreational fisheries become strictly regulated to prevent over-exploitation by the larger number of people and increased leisure time. Supporting and regulating ecosystem services are restored as nutrient and sediment pollution are controlled, native vegetation is improved and invasive species are managed. The critical functions that these services provide are protected by novel markets, institutions and community-based management. Increasing water demand from the larger population growth is mitigated by water use efficiency preventing the construction of additional dams, maintaining catchment ecosystem services.
	There is a focus on social justice, democracy, common property rights and quality of life. Income distribution has become more equitable, education and security improve, resulting in major increases in health and well-being. The built environment is maintained but is re-designed to improve quality, reflecting local aspirations, such as innovative public transport networks. Social capital increases: people look after each other as well as the environment, generating more shared knowledge, awareness and trust, and creating adaptive capacity.

(4) If global climate change is neither managed nor mitigated, there will be no coral cover (*Trashing the Commons*).

What we can also observe is a 'flip' at about mid-century, where the trajectory of coral cover in the *Treading Water* scenario is completely altered and it begins to decline from near-present levels. In interpreting the projections, the following model assumptions need to be borne in mind.

While corals will bleach more often from global warming, the resulting mortality rate is assumed small (i.e., based on GBR historical data). The model further assumes that mortality from bleaching in scenarios with 2 °C warming will not be greater than observed in 1998 and 2002 (+0.7 °C warming), events that resulted in ~5% death of existing corals each time. Thus, the model results rely on the assumption that corals will gradually adapt to warming waters and remain insensitive to ocean acidification. If mortality from coral bleaching remains at 5% every 4 years as the model assumes, a reef may still sustain some coral cover as coral cover can increase by 1–2% per year, if crown-of-thorns outbreaks become infrequent. However, there is presently no evidence for corals adapting to warming waters.

Management of land use will bring some life back to inshore coral reefs; this increases the average coral cover even if coral cover of offshore reefs decreases. Increasing coral cover up until 2050 in the *Best of Both Worlds* and *Treading Water* scenarios assumes that water quality will be greatly improved such that outbreaks of COTS—presently the greatest source of coral mortality—will become rare.

The initial increase in average coral cover in the *Treading Water* scenario is due to improvement of inshore reefs until ultimately bleaching decreases cover of all reefs by 2100. This assumes that offshore reefs decline continuously, inshore reefs increase to reach a maximum by 2050, and that all reefs are in decline from 2050 to 2100 as they are affected by frequent bleaching from increased temperatures between 2050 and 2100.

Coral cover would also be lower than predicted by the HOME model in the *Trashing the Commons* and *Treading Water* scenarios if acidification is taken into account, or if the frequency and/or intensity of cyclones and floods in the GBR increase, as some climate models predict.

3.2.2. Land cover/use

Changes in the extent of terrestrial and marine ecosystems in 2100 relative to the present are summarized for each of the four scenarios (Table 5). The main trends are an intensification of current agricultural and urban land use in *Trashing the Commons*

Table 3
Summary of key characteristics of each scenario.

Scenario and development paradigm	Projected CO_2 emissions/ temperature increase by 2100	Implications for climate change and its mitigation in GBR	GBR 2050 population projections (current population: 1.12 million)
Trashing the Commons Global Empty World; Australia Empty World	850 ppm/3.5 °C	Sea level rise 1 m Sea water pH 7.7 Increased cyclone intensity Erratic water quantity Severe nutrient and sediment pollution Reduced native vegetation extent and condition Increased invasive species	3.0 million, due to industrial expansion and intensification, climate refugees from southern Australia and Asia-Pacific
Free Riders Global Full World; Australia Empty World	350 ppm/<2 °C	Sea level rise ≤ 0.3 m Sea water pH similar (8.0) Cyclone intensity similar Severe nutrient and sediment pollution Reduced native vegetation extent and condition Increased invasive species	2.5 million, some domestic 'lifestyle' immigration from southern Australia
Treading Water Global Empty World; Australia Full World	850 ppm/3.5 °C	Sea level rise 1 m Sea water pH 7.7 Increased cyclone intensity Erratic water quantity Reduced native vegetation extent and condition, and declining water quality, but mitigated by improved land management Increased invasive species	3.0 million, due to industrial expansion and intensification, climate refugees from southern Australia and Asia-Pacific
Best of Both Worlds Global Full World; Australia Full World	350 ppm/<2 °C	Sea level rise 0.3 m Sea water pH 8.1 Cyclone intensity similar Control of nutrient and sediment pollution at 1990 levels after 20% increase mid-century Native vegetation extent and condition improved Invasive species controlled	2.0 million, limited domestic immigration from southern Australia

and *Free Riders*, accompanied by a decline in coastal and marine ecosystems, grazing and production forestry. Diversification into a mix of land uses in *Treading Water* and *Best of Both Worlds* allows the extent of some coastal and marine ecosystems to remain at or return to present levels, though a number of ecosystem types continue to decline in *Treading Water*.

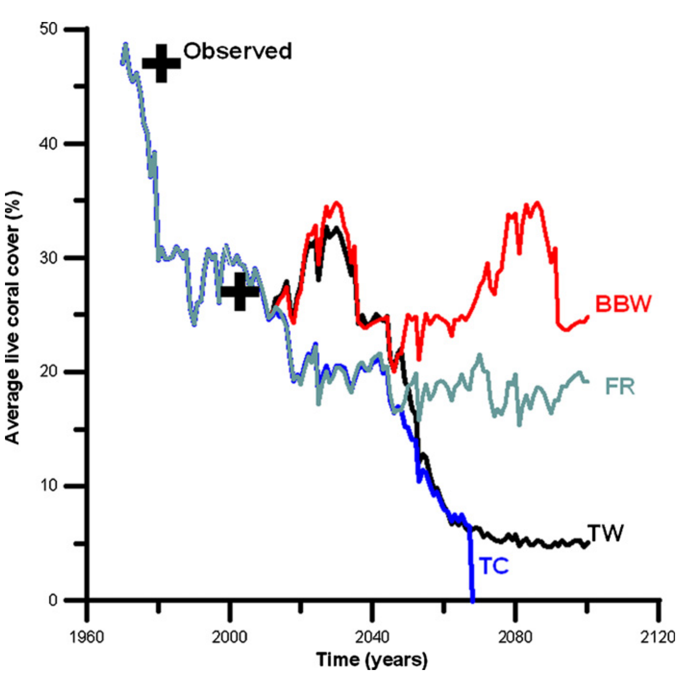

Fig. 5. The predicted average coral cover on 261 reefs between Bowen and Lizard Island to 2100 for the four scenarios: TC = *Trashing the Commons*, TW = *Treading Water*, FR = *Free Riders*, and BBW = *Best of Both Worlds*.
Observational data are from Bruno and Selig (2007).

3.3. Implications for ecosystem services and human well-being

Table 6 presents a summary of change in ecosystem services and human well-being. A well-being indicator was created by adding the arrows for the four scenarios. This indicator showed that overall well-being was lowest in *Trashing the Commons*, followed by *Free Riders*, *Treading Water* and the *Best of Both Worlds*. An economic subset indicator was created by adding the arrows for relative change in population and the arrows for relative change in the quantity of the built environment.

The graph of these two indicators for the four scenarios depicts an inverse linear relationship between the summary well-being and economic subset indicators (Fig. 6.) We emphasize that the comparative ratios of these measures in the four scenarios are of interest, rather than a comparison of the two types of indicators, given the unequal numbers of indicators contributing to each measure.

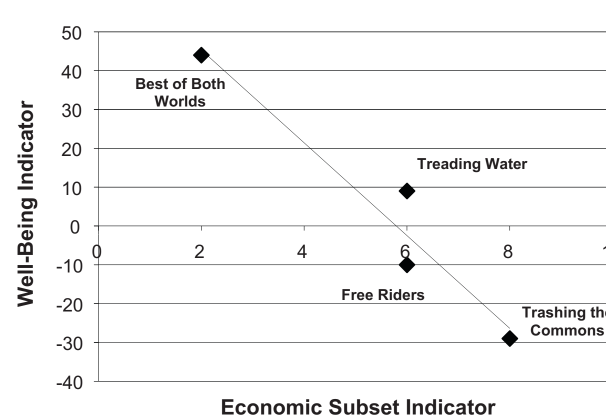

Fig. 6. Summary well-being indicator plotted against economic subset indicator for the four scenarios in 2100. Indicators were derived from Table 6.

Table 4
Outcomes for terrestrial and marine ecosystem services in the GBR in each of the four scenarios.

Scenario	Ecosystem	Ecosystem services			
		Supporting	Provisioning	Regulating	Cultural
Trashing the Commons	Terrestrial	Nutrient cycling stressed	Agriculture intensification and increased cropping area with irrigation due to increasing global population Increased dams for water supplies due to more erratic water supply Mining increases due to increasing global demand Condition of services declining	Water regulation declining with reduced native vegetation cover Carbon storage declining Pollination and disease regulation declines	Tourism maintained Recreational fisheries maintained but greatly reduced catches Biodiversity values decline for non-Indigenous and Indigenous communities Educational and scientific values decline
	Marine	Less than 1% coral cover due to acidification and annual coral bleaching, reefs are dominated by algae Fish biomass and diversity reduced 80% due to over-fishing and loss of coral Nutrient cycling stressed	Commercial fisheries have severely reduced catch Aquaculture increases in the coastal zone Condition of services declining	Storm protection from reef declines, elevating coastal erosion	International reef tourism collapse Recreational fisheries maintained but greatly reduced catches Biodiversity values decline for non-Indigenous and Indigenous communities Educational and scientific values decline
Free Riders	Terrestrial	Nutrient cycling stressed but not as much as *Trashing the Commons*	Moderate agricultural intensification and increased cropping area with irrigation Some increased dams for water supplies	Water regulation declining with reduced native vegetation cover, but less than in *Trashing the Commons* Carbon storage declining Pollination and disease regulation declines, but less than in *Trashing the Commons*	Tourism maintained Recreational fisheries increased but based on reduced biomass Biodiversity values decline but not as much as in *Trashing the Commons* or *Treading Water* Educational and scientific values decline
	Marine	Coral cover is 20% due to poor local management and declining water quality Fish biomass and diversity reduced 70% due to overfishing Nutrient cycling stressed but not as much as *Trashing the Commons*	Commercial fisheries have severely reduced catch Aquaculture increase in the coastal zone	Storm protection from reef declines, elevating coastal erosion	International reef tourism collapses but some retained Recreational fisheries increased but based on lower biomass Biodiversity values decline but not as much as in *Trashing the Commons* or *Treading Water* Educational and scientific values decline
Treading Water	Terrestrial	Nutrient cycling stressed but not as much as *Trashing the Commons*	Mining increases, but alongside renewable energy development Agriculture intensification and increased cropping area with irrigation, but not as intensive as *Trashing the Commons* Increased dams for water supplies	Water regulation declining with reduced native vegetation cover, but not as much as in *Trashing the Commons* Carbon storage declining Pollination and disease regulation declines, but not as much as in *Trashing the Commons*	Tourism maintained Recreational fisheries increased but based on reduced biomass Biodiversity values decline but not as much as in *Trashing the Commons* Educational and scientific values decline
	Marine	Coral cover 20% by 2050, declining to <5% by 2010 due to coral bleaching and acidification Fish biomass reduced by 50% Nutrient cycling stressed	Commercial fisheries take over tourism as main marine use of GBR, but reduced catch Aquaculture increase in the coastal zone but impact mitigated by good management	Storm protection from reef declines, elevating coastal erosion	International reef tourism collapses but some retained Recreational fisheries increased but based on lower biomass Biodiversity values decline but not as much as in *Trashing the Commons* Educational and scientific values decline
Best of Both Worlds	Terrestrial	Nutrient cycling maintained	Increase in native forestry Renewable energy promoted Agriculture maintained with improved management Water supplies maintained without new dams	Water regulation maintained with increased native vegetation cover and protected areas Carbon storage increased Pollination and disease regulation increases	Tourism grows with increased protected areas Recreational fisheries increase based on similar biomass but better managed Biodiversity improves with restoration Educational values maintained or improved

Table 4 (*Continued*)

Scenario	Ecosystem	Ecosystem services			
		Supporting	Provisioning	Regulating	Cultural
	Marine	Coral cover returned to 25% (1990 levels) Fish biomass recovering from 80% mid-century Nutrient cycling maintained	Commercial fisheries maintained but more sustainable Low-impact aquaculture developed	Storm protection from reef maintained	International reef tourism collapses but some retained Recreational fisheries increased based on similar biomass but better managed Biodiversity values maintained Educational values maintained or improved

4. Discussion

4.1. Analysis of scenarios

While *Trashing the Commons* and *Best of Both Worlds* represent distinctly different futures for the GBR, the other two scenarios diverge in ways that reveal much about the dynamics that may shape the future of the region. We revisit our conceptual framework to discuss results of the four scenarios, beginning with ecosystems.

For marine ecosystems, the model suggests that until 2050, mitigation of climate change impacts on reefs through regional land management has a good chance of maintaining coral cover. After 2050, the effects of global climate change are likely to outweigh regional mitigation, as evident from the much higher levels of coral cover in *Free Riders* than in *Treading Water*. Despite this, *Treading Water* illustrates that it is possible to maintain a minimal amount of coral reef by the end of the century even in the absence of a change in global climate change policy. However, there are probable threshold levels for coral cover, beyond which the GBR will become a fundamentally different system by 2100 if climate change reaches the upper levels described in the *Trashing the Commons* and *Treading Water* scenarios.

In terrestrial systems, ecosystem types exhibit unique responses to the four scenarios; natural forest responds negatively to climate change (declining in *Trashing the Commons* and *Treading Water*) but has great potential to increase where there is effective land management and minimal climate change (*Best of Both Worlds*). Some ecosystem types appear to be more sensitive to climate change than to intensive or inadequate land management (i.e., natural forest, lakes and rivers, marshes and wetlands), while for others the opposite is true (i.e., mangroves, swamps). This suggests that management that can respond to pressures at both scales is needed to maintain the full range of terrestrial ecosystem types. Links between marine and terrestrial ecosystems also need to be taken into account, which were not feasible to address in depth in this analysis as we lacked time series data for terrestrial ecosystems. Increased agriculture and urban land use in the catchment are likely to erode terrestrial ecosystem services, but relationships between catchment activities and water quality in

Table 5

Change in extent of terrestrial and marine ecosystems in 2100 relative to the present for each scenario. Upward-pointing arrows indicate an increase in the extent of a type of land cover/use, and downward-pointing arrows indicate a decrease. The number of arrows (between 1 and 5) indicates the amount of change. Arrows pointing left and right indicate no change.

	Land cover/Land use	Current area (% of catchment)	Trashing the Commons	Free Riders	Treading Water	Best of Both Worlds
Upland	Natural Forest	12.9	↓	↔	↓	↑↑↑↑↑
	Lakes/river	0.4	↓	↔	↓	↔
Coastal	Mangroves	0.9	↓↓	↓	↔	↔
	Marsh/wetland	0.4	↓↓↓↓	↓↓↓	↓↓↓↓	↔
	Swamp	0.1	↓	↓	↔	↔
	Saline coastal flat	n/a	↓↓	↓	↓	↔
	Estuary/coastal waters	n/a	↔	↔	↔	↔
Marine	Coral	n/a	↓↓↓↓↓	↓↓	↓↓↓	↔
	Seagrass	n/a	↓	↓	↔	↔
	Shelf	n/a	↔	↔	↔	↔
	Islands	n/a	↓↓	↔	↓↓	↔
Agriculture/Urban	Grazing	74.6	↓↓	↓	↑↑↑	↔
	Production forestry	5.1	↓↓↓	↓↓	↓↓↓	↑↑
	Intensive agriculture	3.2	↑↑↑↑↑	↑↑↑↑	↑↑↑	↔
	Sugarcane	1.3	↔	↔	↔	↔
	Mining	0.2	↑↑↑	↑↑	↔	↓↓
	Urban/services/utilities	0.7	↑↑↑↑↑	↑↑↑↑	↑↑↑	↑↑
	Reservoir/dam	0.1	↑↑↑↑	↑↑	↔	↓↓

Table 6
Summary of impacts on ecosystem services and human well-being in 2100 relative to the present, averaged for terrestrial and marine ecosystems, for each scenario. ES = ecosystem services, BE = built environment. Upward-pointing arrows signify an increase in the value of an indicator, and downward-pointing arrows signify a decrease. The number of arrows (between 1 and 5) indicates the amount of change. Arrows pointing left and right indicate no change. The summary well-being indicator was calculated by summing upward arrows (each equivalent to +1) and downward arrows (each equivalent to −1) for all indicators. The economic subset indicator was calculated by summing the arrows for population and quantity of built environment.

	Capitals	Trashing the Commons	Free Riders	Treading Water	Best of Both Worlds
ES	Supporting	↓↓↓↓	↓↓↓	↓↓↓	↑↑
	Regulating	↓↓↓↓↓	↓↓↓	↓↓↓	↑↑↑
	Provisioning	↓↓	↓	↓	↑↑
	Cultural	↓↓↓↓↓	↓	↓↓↓	↑↑
Human well-being	Equity	↓↓↓↓	↓↓	↑	↑↑↑
	Participation	↓↓	↑	↑↑	↑↑↑
	Security/safety	↓↓↓	↔	↑↑	↑↑↑
	Democracy	↓↓↓	↓↓↓	↑↑	↑↑↑
	Networks	↑↓	↑↓	↑↓	↑
	Culture	↓	↓	↑	↑↑↑
	Institutions	↑↓	↑↓	↑	↑↑↑↑
	Education	↓↓	↓	↑	↑↑↑
	Health	↓↓	↓	↑	↑↑↑↑↑
	Professional skills	↑	↑	↔	↑
	Job security	↓	↔	↑	↑↑
	Population	↑↑↑↑	↑↑↑	↑↑↑	↑↑
BE	Quantity	↑↑↑↑	↑↑↑	↑↑↑	↔
	Quality	↓↓↓↓	↓↓	↑	↑↑
	Well-being Indicator	-29	-10	9	44
	Economic Indicator (Pop. + Built Quantity)	8	6	6	2

marine systems remain somewhat less tractable (Fabricius and De'ath, 2004; Brodie et al., 2007).

Ecosystems and their services are essential support systems for human well-being, yet the relationships between them are complex (MA, 2003). At best, improvements in the four categories of ecosystem services are moderate, but improvements in some of the human well-being indicators are more substantial (e.g., health and institutions). While conditions of ecosystem services can decline rapidly, recovery is often very slow, if it happens at all (Scheffer et al., 2001). By comparison, aspects of human well-being can improve relatively quickly. For example, health improves in *Treading Water* even though all ecosystem services decrease. In *Free Riders* and *Trashing the Commons*, on the other hand, health declines, which may be linked to declines in ecosystem services. It is worth noting that in *Trashing the Commons*, in which all ecosystem services decline the most, indicators of equity, participation, security, education, health, job security and quality of the built environment are also at their lowest levels. Thus, we see that modest improvements in human well-being are possible even while ecosystem services decline, but only where there is strong regional management. In a departure from this trend, cultural ecosystem services are worse off in *Treading Water* than in *Free Riders*, as biodiversity values decline as a result of climate change.

Population and the built environment, the economic subset indicators, fare the same in *Free Riders* and *Treading Water*, but outcomes for the GBR in terms of total well-being by 2100 are better in *Treading Water* than in *Free Riders*, reflecting higher levels of human well-being and regional actions to improve ecosystem services and well-being. *Trashing the Commons* and *Best of Both Worlds* occupy opposite ends of a continuum between total well-being and economic well-being, signifying that one end cannot be achieved without compromising the other. Somewhat paradoxically, to achieve the higher levels of total well-being in a *Best of Both Worlds* scenario, GBR inhabitants will be required to make some sacrificial lifestyle changes, which may negatively impact their well-being, at least in the short term. Larson's (2009) survey of well-being priorities among GBR residents should be borne in mind, which shows that while well-being is subjective and wide-ranging, income levels are highly valued, though family and societal relations and health services even more so.

Impacts on ecosystem services and human well-being in turn have feedbacks on drivers and in essence become drivers for further change. Adaptation, which may mediate global impacts on ecosystem services and human well-being, is likely to be key in these scenarios. For example, in *Free Riders*, in which Australia becomes a Pariah state in the eyes of the world, a more limited export market drives innovation and resourcefulness. In *Trashing the Commons*, individuals may eventually take action to improve a compromised sense of well-being. Alternatively, a trigger for change may come from ecological crisis (Gunderson et al., 2002). When such action reaches a tipping point, change may begin to occur in policies and management practices. Hence, a seemingly undesirable pathway can become a desirable one if crisis inspires positive change; however, some irreversible damage may happen along the way. Better understanding is needed of adaptation and adaptive capacity among individuals and industries in the GBR. From a methodological point of view, scenarios need to be flexible enough to accommodate such adaptations.

4.2. Implications for management of GBR

Following the *Free Riders* pathway—that is, failing to mitigate climate change at a regional scale although global climate change is being managed—in the belief that the GBR will be moderately intact by 2100 as long as the rest of the world is doing its part in combating global climate change falls afoul of 'short-termism' (Cocks, 1999). There are many uncertainties associated with climate change impacts and their possible interactions across scales. Our scenario analysis may be optimistic; we simply cannot state with any confidence whether there is a point of no return for marine ecosystems, beyond which the writing is on the wall with regard to climate change. Though these thresholds may be unknown, it will be important to determine a 'safe operating space' (Rockström et al., 2009) for this system, based on normative judgements about uncertainty and risk.

Conversely, our analysis may be pessimistic, but there are additional arguments for a proactive approach to climate change mitigation: one is based on the benefits for terrestrial ecosystems in the catchment and the many industries that depend on them (Marshall, 2010), and a second on the benefits for health, security, culture and other components of human well-being. Furthermore, empirical data and models indicate that threats to the GBR clearly need to be addressed in an integrated way, such that the whole social-ecological system is recognised (Olsson et al., 2008).

Global climate change is not easily addressed at regional and local scales, yet this is where many of its pressures are most profoundly felt (Wilbanks and Kates, 1999). This analysis points to a need to design management responses for the GBR region that account for cross-scale processes even if appropriate global responses and institutions are inadequate. It also implies that responses of other actors, such as civil society and industry, may need to play a role. There must also be temporal scale matching of institutions and the processes they are intended to address so that they can adequately capture feedback (Wilson, 2006). Tighter coupling is needed between processes of water quality management and climate change mitigation in the GBR, though they operate at different spatial and temporal scales.

5. Conclusion

The scenario approach we describe above is novel for the GBR, whereby: (1) global climate change projections were downscaled for the region; (2) a combination of qualitative and quantitative scenarios were developed that explored the region as a whole, rather than focusing only on catchments, reef ecosystems or economic sectors; (3) the scenarios were framed by the key uncertainties underlying climate change in the GBR—global and Australian development pathways. It is this third aspect in particular that is especially important, as uncertainties related to worldviews are those that often lead to abrupt, surprising outcomes (Janssen, 2002).

These aspects relate mainly to the methods of our scenario analysis, but its greatest value, and global relevance, may lie in the process, in two ways in particular. First, scenarios such as these are important for supporting (often urgent) decision-making in a data-constrained environment. Scientists and management agencies repeatedly urge that action on climate change needs to be taken sooner rather than later (GBRMPA, 2009; Christoff, 2010), despite the absence of complete data sets and knowledge, a situation which the scenario approach can accommodate. Second, scenarios are important for stimulating futures thinking among a region's myriad stakeholders (including scientists from different disciplines and institutions), and in doing so, fostering communication among each other (Wollenberg et al., 2000; Lebel et al., 2005; Bohensky et al., 2011).

That said, scenarios that are intended to serve both scientific and political endeavors tend to trade off credibility, salience and legitimacy, and balancing these is imperative (Girod et al., 2009). Our scenarios were developed in a workshop involving a large group of scientists with a small representation from GBRMPA, Queensland government, industry and other stakeholders. Consequently the exercise was primarily an exploration of scientific understanding of the dynamics that may shape the future of the GBR. This is a legitimate objective of scenario analysis (Biggs et al., 2007) and the process was valuable for enhancing and challenging this understanding, as the scenarios revealed a more nuanced picture of the potential implications of global climate change and regional mitigation in the GBR than contemporary 'doomsday' narratives allow (Doulton and Brown, 2009; O'Neill and Nicholson-Cole, 2009). This broadened understanding includes unintended consequences of climate change and other important drivers, and trade-offs, with some better outcomes for particular ecosystems, populations or economic sectors, and some worse outcomes for others.

The very full agendas of regional decision-makers means that coming to the table with at least a demonstrative example of scenario analysis is often an effective starting point for engagement. 'Ex-post' approaches to participation may be criticized, but it is important to view scenarios as evolving conversations through an iterative process with opportunities for updating new data, knowledge and problem conceptualizations. In the future, we might look to Shaw et al. (2009) whose scenario exercise in British Columbia used visualizations of iconic places to contextualize global climate change and make it more meaningful regionally. However, the challenge remains to determine how to engage the broad range of stakeholders in the GBR on the issue of climate change, from local primary stakeholders (e.g., tourists, fishermen, farmers) to state and regional government, to global interests. Given the complexity of the scales of governance, the cross-scale flows of ecosystem services and linked beneficiaries, deciding how engagement, and indeed identification of appropriate agents of change should start, is the primary job at hand.

Olsson et al. (2008) identified a policy window as a key facet of the successful re-zoning of the GBR, and it is possible that such an opportunity to respond to climate change may emerge in the future, triggered, for example, by a massive coral bleaching event or an extreme tropical cyclone. Stakeholders who are already familiar with the scenario framework and storylines used in our workshop may be better prepared for these opportunities. Until such a window opens, the most feasible approach may be to engage with the Reef Plan and Reef Rescue processes for water quality management, which are already operational.

A great benefit of scenarios lies in their ability to raise awareness of the possibilities and limits of human agency to steer the future in a desired direction. As Doug Cocks observed:

> 'Tomorrow's world may be a bugger of a place which we can do little to avoid but, if we try to make it better, it is unlikely to be worse than if we had not tried. We are both future *makers* and future *takers*. We are constantly adapting and reacting to powerful social, political, economic and environmental forces. If, at the end of the present inquiry, we cannot avoid concluding that the future is being determined by powerful irresistible

> forces we do not like—all take and no make—then such knowledge might at least lessen the pain of living with the consequences (Cocks, 1999, p. xv)

As Australia and the GBR region engage in climate policy and mitigation processes, this analysis underscores the need to adopt more proactive precautionary attitudes to dealing with uncertainty. The future is undeniably uncertain; what will matter is whether the region is prepared to accept uncertainty, and if not, what kind of outcomes the GBR's stakeholders, from local to global, are willing to live with.

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Appendix A. Global scenarios

The Great Transition Initiative (Raskin et al., 2002)

An ongoing effort with its beginnings in the 1990s (Gallopín et al., 1997) (http://gtinitiative.org/), the scenarios have changed name and number over time, but the current set involves four major scenarios: *Fortress World*, *Market Forces*, *Policy Reform*, and *Great Transition*.

The *Fortress World* scenario is a variant of a broader class of Barbarization scenarios, in the hierarchy of the Global Scenario Group (Gallopín et al., 1997). Barbarization scenarios envision the grim possibility that the social, economic and moral underpinnings of civilization deteriorate, as emerging problems overwhelm the coping capacity of both markets and policy reforms.

The *Market Forces* scenario is a story of a market-driven world in the 2lst Century in which demographic, economic, environmental and technological trends unfold without major surprise relative to unfolding trends. Continuity, globalization and convergence are key characteristics of world development—institutions gradually adjust without major ruptures, international economic integration proceeds apace and the socioeconomic patterns of poor regions converge slowly toward the development model of the rich regions.

The *Policy Reform* scenario envisions the emergence of strong political will for taking harmonized and rapid action to ensure a successful transition to a more equitable and environmentally resilient future. It explores the requirements for simultaneously achieving social and environmental sustainability goals under high economic growth conditions similar to those of *Market Forces*.

The *Great Transition* scenario explores visionary solutions to the sustainability challenge, including new socioeconomic arrangements and fundamental changes in values. This scenario depicts a transition to a society that preserves natural systems, provides high levels of welfare through material sufficiency and equitable distribution, and enjoys a strong sense of local solidarity.

An interactive web site allows users to visualize and explore the scenarios (http://www.tellus.org/results/results_World.html). The descriptions of these scenarios in the published books and web sites are the most extensive of the scenario studies mentioned here, and probably the most extensive of any existing scenario exercise. The status and trends of over 40 variables are plotted for each scenario, including several variables related to ecosystem services (i.e. CO_2 emissions, water use, forested area) and an overall "Quality of Development Index" that is similar in structure to the Genuine Progress Indicator (GPI) and other indices of societal well-being.

The Millennium Ecosystem Assessment (MA, 2005)

The Millennium Ecosystem Assessment (MA) scenarios used the two axes of global connectedness (from highly connected to disconnected), and approaches to ecosystem services management (from reactive to proactive) to evaluate the future status of ecosystem services and human well-being (MA, 2005). The two globally connected scenarios were: (1) *TechnoGarden*, which envisions a globally connected world relying strongly on environmentally sound technology, using highly managed, often engineered, ecosystems to deliver ecosystem services, and taking a proactive approach to the management of ecosystems in an effort to avoid problems before they emerge, and (2) *Global Orchestration*, which envisions a globally connected society that focuses on global trade and economic liberalization and takes a reactive approach to ecosystem problems, but that also takes strong steps to reduce poverty and inequality and to invest in public goods such as infrastructure and education. The two regionalized and disconnected scenarios were: (3) *Order from Strength*, which envisions a regionalized and fragmented world, concerned with security and protection, emphasizing primarily regional markets, paying little attention to public goods, and taking a reactive approach to ecosystem problems, and (4) Adapting Mosaic, which envisions that regional watershed-scale ecosystems are the focus of political and economic activity. Local institutions are strengthened, local ecosystem management strategies are common, and societies develop a strongly proactive approach to the management of ecosystems.

All but the *Order from Strength* scenarios showed that significant changes in policy can partially mitigate the negative consequences of growing pressures on ecosystems, but that the changes required are large and not currently under way. Some ecosystem services and well-being improve in these three scenarios, but the largest increases across all services are in the Adapting Mosaic scenario. Climate change is envisioned to affect all of the scenarios, but to varying degrees based on policies to mitigate it.

Four Future Scenarios for New Zealand: Work in Progress (Landcare Research Scenarios Working Group, 2007)

Researchers in New Zealand and an advisory group created four scenarios along the two axes of resources (depleted or plenty) and identity (individual or cohesion). The two plentiful resource scenarios were titled: (A) *Fruits for a Few*, where a focus on individual identity leads to tight resource control, with benefits held in the private sector and costs spread on the wider public and (B) *Independent Aotearoa*, where a focus on social cohesion leads to a dynamic cohesive society, seeing itself as a global citizen. While outward looking, it remains critical and is confident enough to be distinctly different as a South Pacific nation. The two depleted resource scenarios are: (C) *New Frontiers*, where the focus on individualistic values, defined by visible financial status, rather than by family and cultural traditions leads to a fragmented society where the losers feel there is unfairness while the winners enjoy their freedoms as consumers and (D) *Living on No. 8 Wire*, where a focus on social cohesion leads government to intervene to manage trade-offs between economic gain and environmental degradation, to increase trade barriers and to promote equitable redistribution.

Like the Great Transition Initiative and MA scenarios, the New Zealand scenarios were described in great detail, including their impacts on ecosystem services and quality of life. This exercise included a survey of attitudes toward the scenarios. A group of participants was asked in a game playing exercise about which scenario they thought New Zealand was presently in, which scenario it was headed toward, and which scenario they would most like to see realized. The results were quite dramatic. Most participants thought New Zealand was currently in the *Fruits for a Few* scenario and that it was headed toward the *New Frontiers* scenario, but that they overwhelmingly preferred the *Independent Aotearoa* scenario, where quality of life was enhanced by social cohesion and resource management.

Appendix B. Australian scenarios

Futurist Doug Cocks invoked a fundamental choice for Australia: would it be a future 'maker' or a future 'taker'? (Cocks, 1999). Cocks developed five 'big-picture' scenarios for the country, three of which he considered positive pathways that could all realistically achieve the goal of high quality of life for most present and future Australians, without abandoning the current democratic, capitalist society with a mixed economy. One way to do this is *Going for Growth*, whereby very high per capita income will create the money needed to protect the environment and to eliminate poverty. An alternative pathway is *Conservative Development* embraces interventionist industry policies derived from 'new growth' thinking and faith in the capacity of government to contribute strongly to solving the problems of low economic growth, unacceptable levels of life opportunities and poor environmental quality through a 'tax and spend' strategy. *Post-Materialism*, by contrast, involves a change in the deep structure of society, via the distribution and use of decision-making power in organisations, institutions and social groupings. New regional governments would increasingly edge out state governments, and worker ownership and industrial democracy would ensure corporate social responsibility. However, two less desirable pathways could also unfold: *Struggling to Cope* describes what happens when a complex, path-dependent society like Australia encounters multiple crises in a short amount of time. In *Muddling down,* quality of life declines slowly at the hands of reactive governments which act only in response to extreme political pressure, or gridlocked governments which who are hostages to major interest groups.

In 2005, the Business Council of Australia also developed scenarios that focused on relationships between Australia's diverse populations and with the rest of the world (BCA, 2004). Using the metaphor of the ocean, scenarios were constructed around both endogenous drivers of continued growth and dominance of Sydney and the ageing of Australia's population, and exogenous drivers of continued global political dominance of the United States, and the ability of technology to remove some of the constraints arising from the great distance between Australia and its major trading partners. These drivers act together to create three major challenges, or uncertainties in Australia's future, related to: social cohesion and shared values between generations and between different cultural, ethnic and socio-economic groups, and the stability of the Asia-Pacific region. The *Riding the Wave* scenario explores the possibility of a breakdown in trust between Australian people and institutions, *Stormy Seas* posits reduced security in the Asia-Pacific region, and *Changing the Crew* depicts intergenerational tensions within Australia but increased economic and cultural relatedness between the younger generation and the world outside.

The Energy Futures Forum brought together a wide group of representatives from energy companies, mining companies, environmental groups, banks and unions to develop qualitative and quantitative scenarios to identify a range of plausible options for Australia's energy sector (Energy Futures Forum, 2006). Among the nine Energy Futures Forum scenario narratives (Delaney, 2006), environmental crisis is most apparent in the *Day After Tomorrow* scenario, with the narrative describing water wars in major rivers around the world and conflict over access to fisheries, and in Australia, coastal inundation and coral bleaching in the Great Barrier Reef (GBR), with a subsequent loss of tourism expected. In the *Clean Green Down Under* scenario, Australia by 2050 has reduced its greenhouse gas emissions to 80% below 1990 levels in response to several major climate events in the early 2010s that bring about the end of global opposition to addressing climate change. *Power to the People* reveals how new farming practices (i.e. aquaculture and organic crops) develop in Australia in response to ecological change, such as more extreme climate patterns, further outbreaks of diseases and the need to curtail water consumption. In *Centralised Failure*, climate change and high adaptation costs bring smaller towns and even Canberra to the point of collapse, requiring the capital to be relocated to a less drought-prone location.

The Avon River Basin scenario project (O'Connor et al., 2004) in the Western Australia Wheatbelt sought to identify critical issues and drivers of change relevant to community efforts to improve the regional prospects for present and future generations of the basin to 2050. The process, convened by a Wheatbelt resident and landholder, identified twenty-two critical drivers of change, which included land, infrastructure, alternate fuels, education, plant industries and demographics. In a ranking exercise, project participants identified access to new markets and whether environmental problems (namely salinity) improve or degrade as the most uncertain and important drivers. In *Grain and Drain*, salinity damages infrastructure, elevating repair costs, while climate change (of 3–6 °C across the basin) and rising sea levels encourage some Perth residents to settle in the Avon River Basin. In *Saline Growth*, similar temperature increases are experienced but society responds proactively through social and economic diversification. The *Landcare Bounty* and *Harmony with Prosperity* scenarios describe slower environmental decline, with temperatures increasing only 1–2 °C, and focus respectively on sustainable land use and developing new markets.

Scenarios conducted for the GBR include WWF Australia and the Queensland Tourism Industry Council's scenarios based on the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel for Climate Change. The WWF approach to scenarios was to focus on what they considered to be credible eventualities in order to plan responses, rather than to explore uncertainties. They developed successive storylines for Australia, the GBR, reef-based industries (tourism and fisheries), and other industries driving the regional economies, culminating in numerical projections for each scenario for tourism and fisheries and the economic impact on five GBR regions (Hoegh-Guldberg and Hoegh-Guldberg, 2008).

Another scenarios initiative for the GBR was undertaken by CSIRO (Bohnet et al., 2008). The scenarios were developed for the catchment-to-reef system based on a literature review and interviews with 47 regional leaders from academia, government, non-governmental organizations and industry. These scenarios focused on the two key uncertainties that were most frequently mentioned in the interviews: the nature and timing of a climate change event (whether a major climate event, such as a Category 5 cyclone, occurs within the next five years or is delayed until later), and the nature of regional governance (whether driven mainly by environmental concerns in the region or by the global economy). The plausibility of the scenarios and their implications for research and knowledge, environmental regulation, infrastructure and planning, industry, production systems and Indigenous livelihoods were explored with key GBR stakeholders, including policy-makers, natural resource managers, Indigenous Traditional Owners, science advisors and industry representatives, in a one-day workshop.

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