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The 'Great Southern Reef': social, ecological and economic value of Australia's neglected kelp forests

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Abstract. Kelp forests define >8000 km of temperate coastline across southern Australia, where ~70% of Australians live, work and recreate. Despite this, public and political awareness of the scale and significance of this marine ecosystem is low, and research investment miniscule (<10%), relative to comparable ecosystems. The absence of an identity for Australia's temperate reefs as an entity has probably contributed to the current lack of appreciation of this system, which is at odds with its profound ecological, social and economic importance. We define the 'Great Southern Reef' (GSR) as Australia's spatially connected temperate reef system. The GSR covers ~71 000 km^2 and represents a global biodiversity hotspot across at least nine phyla. GSR-related fishing and tourism generates at least AU$10 billion year^{-1}, and in this context the GSR is a significant natural asset for Australia and globally. Maintaining the health and ecological functioning of the GSR is critical to the continued sustainability of human livelihoods and wellbeing derived from it. By recognising the GSR as an entity we seek to boost awareness, and take steps towards negotiating the difficult challenges the GSR faces in a future of unprecedented coastal population growth and global change.

Additional keywords: ecosystem services, ecosystem values, temperate reef.

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The Great Southern Reef – the case for an identity

Temperate reefs are hard-bottom marine ecosystems found in cool waters between the tropics and the poles. Temperate reef ecosystems are diverse, spanning supralittoral lichen-encrusted boulders to sponge gardens on rocky outcrops in the deep oceans. Worldwide, where enough light penetrates to the seafloor, healthy temperate reefs are usually dominated by 'kelp forests' – highly productive, structurally complex communities of canopy-forming seaweeds of the orders Laminariales, Desmarestiales and Fucales (Bolton 2010; Steneck and Johnson 2013). Depending on light, waves and grazers, kelp forests are found from the shoreline down to depths of 30–40 m (Marzinelli *et al.* 2015), but can be found at depths >60 m in some regions (e.g. Graham *et al.* 2007). Here, we recognise the diversity of temperate reef ecosystems, but focus primarily on kelp forests as they prevail in shallow and coastal waters, where most human attention and activity is concentrated.

In Australia, shallow (<30 m) temperate reefs are defined largely by the distribution of *Ecklonia radiata* kelp forests (Fig. 1), which span more than 8000 km of coastline from the subtropical waters of northern New South Wales (~28.5°S), down the east coast of mainland Australia, around Tasmania, along Australia's southern coastline and north as far as Kalbarri (27.7°S) in Western Australia (Table S1) (Underwood *et al.* 1991; Connell and Irving 2008; Wernberg *et al.* 2011; Marzinelli *et al.* 2015). Most of Australia's kelp-dominated temperate reefs lie within the 'coastal zone' under state jurisdiction (3 nautical miles or 5.5 km from shore), and are therefore managed independently by the five states in which they occur (Fig. 1). Perhaps as a consequence, Australia's

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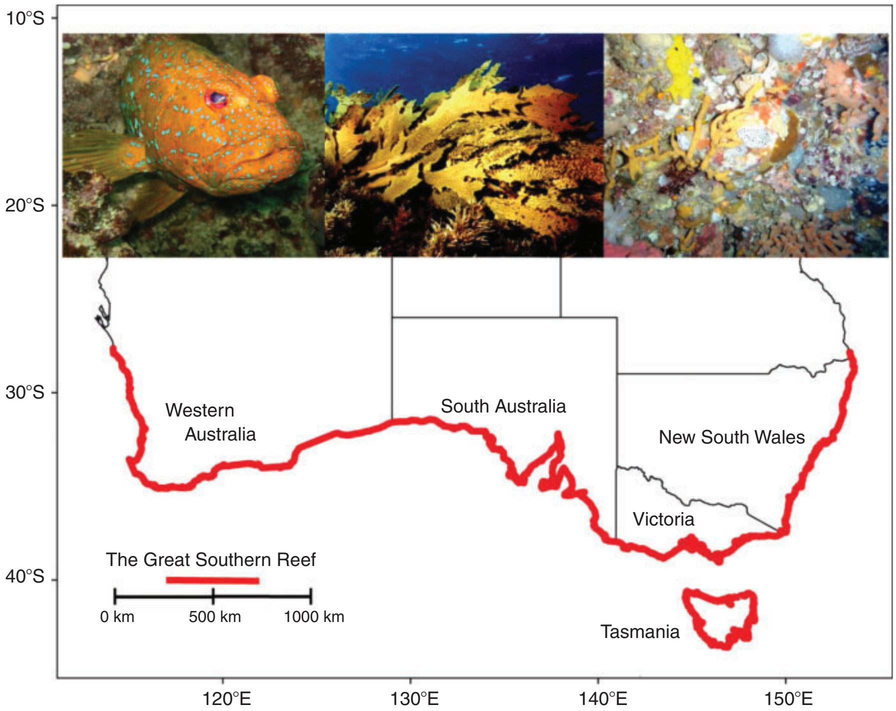

Fig. 1. The Great Southern Reef (GSR) straddles five states across the southern coastline of the Australian continent. Rocky reefs run almost continuously around the southern coastline, where kelp forests dominated by the small common kelp (*Ecklonia radiata*, middle) are a defining feature of the GSR. The reef is home to some of the most unique temperate marine organisms in the world, such as the endemic harlequin fish (*Othos dentex*, left) and myriad invertebrates (right) (photographs: T. Wernberg).

temperate reefs have long been perceived and managed in local contexts, without broader recognition of their significance as an interconnected system. This lack of identity stifles public and political awareness about their importance, not only of their ecology *per se*, but also their importance to the livelihoods of millions of Australians who live, work and engage in recreation around them, and in providing valuable ecosystem services to Australians.

Just as the Great Barrier Reef (GBR) is recognised as an entity made up of more than 2900 individual reefs dominated by corals (Day 2002), Australia's temperate reefs should be considered collectively as an entity made up of thousands of kilometres of rocky temperate reefs, dominated by kelp forests and interconnected through oceanographic (Coleman *et al.* 2011; Wernberg *et al.* 2013*a*), ecological (Irving and Connell 2006; Connell and Irving 2008; Vanderklift and Wernberg 2008) and evolutionary (Phillips 2001) processes – truly a Great Southern Reef (GSR). Here we show that lack of awareness and investment in research focussed on temperate reefs is at odds with the social, ecological and economic significance of the GSR. Australians ignore the GSR and its contribution to our society at our peril, but current levels of scientific engagement and public awareness threaten the health and future function of this significant integrated marine ecosystem. A multiscale view of the GSR as an integrated system would help advance management approaches that recognise both regional differences (Connell 2007), connectivity and ecosystem values (Magris *et al.* 2014), and assist the marine planning process based on the principles of Comprehensiveness, Adequacy and Representativeness (Day *et al.* 2003; Lourie and Vincent 2004) for Australian waters.

The ecological setting

The Great Southern Reef is a global biodiversity hotspot for multiple taxa including seaweeds, sponges, crustaceans, chordates, bryozoans, echinoderms and molluscs (Tables 1, S2) (Bolton 1994; O'Hara and Poore 2000; Kerswell 2006; Barnes and Griffiths 2008; Shenkar and Swalla 2011; Poore and Bruce 2012; Stöhr *et al.* 2012; Van Soest *et al.* 2012). In addition it is estimated that tens of thousands of species are yet to be discovered and described (Butler *et al.* 2010; Appeltans *et al.* 2012; Van Soest *et al.* 2012), many of which could play important functional roles within the GSR (e.g. Knudsen and Clements 2013). Importantly, many of the species found on the GSR make use of both the temperate reef habitat itself and adjoining inter-reef habitats such as seagrass meadows in shallow waters and the sponge 'gardens' that characterise deeper rocky reef habitats. As well as being important assemblages in their own right, these intermediary habitats facilitate connectivity among reefs (Vanderklift and Wernberg 2008) and act as nursery grounds for many species (Jenkins and Wheatley 1998).

A remarkable feature of the biodiversity of the GSR is the high rate of endemism within many taxa. For seaweeds, for example, the GSR is a global hotspot of endemism at the genus level (Kerswell 2006), indicating deep evolutionary isolation since the Oligocene that has resulted in unique and diverse biota

Table 1. Physical, biological and economic attributes of the Great Southern Reef
For details and data sources see Tables S1–S5. All dollar values are AU$

Physical characteristics	
Area (0–30-m depth)	71 389 km^2
Coastline length	8100 km
Human population	15 890 000
Biodiversity and endemism	
Seaweeds	Richness = 978[A], endemism = 40–77% (1)
Invertebrates	Richness = 4100, endemism = 22–56% (1–4)
Fishes	Richness = 731, endemism = n/a
Commercial fisheries	
Rock lobster	Catch = 9199 t, gross production value = \$376.3 million $year^{-1}$
Abalone	Catch = 3614 t, gross production value = \$136.3 million $year^{-1}$
Recreational fisheries	
Coastal waters	Participants = 724 735, revenue = \$553.8 million $year^{-1}$
Economic importance of tourism	
Metropolitan	Expenditure = \$28 196 million $year^{-1}$, importance = 2.4% of revenue
Regional	Expenditure = \$9829 million $year^{-1}$, importance = 7.4% of revenue

[A]Wernberg *et al.* (2013*a*) reported 1499 species of seaweeds across southern Australia. This is the most recent and up-to-date estimate of seaweed species richness for Australia's temperate seaweed flora.

(Hommersand 1986). An estimated 77% of the 565 species of red seaweed found on the GSR are not found anywhere else on Earth (Phillips 2001), whereas the rates of endemism for most other phyla range between 30 and 60% of the total species pool (Tables 1, S2).

The physical driver behind the GSR's high diversity and endemism is thought to be the stable climatic and geological history it has experienced over the past 50 million years (cf. the biodiversity hotspot in the tropical Indo-Pacific: Bellwood and Meyer 2009) along with its geographical isolation (Phillips 2001; Langlois *et al.* 2012). The ecology of the GSR is shaped in large part by boundary currents that flow poleward along both coasts of Australia, transporting warm nutrient-poor water across Australia's temperate coastline (e.g. Wernberg *et al.* 2013*a*). The Leeuwin Current flows southwards down the west coast and wraps along the southern coastline of the continent, whereas the East Australian Current extends down the east coast and penetrates along the east coast of Tasmania during summer (Condie and Dunn 2006). These currents play an important role in the connectivity of larvae and propagules throughout the GSR (Condie *et al.* 2005; Coleman *et al.* 2011) and maintain relatively stable climatic conditions over seasonal and evolutionary time scales (McGowran *et al.* 1997; Condie and Dunn 2006). Interestingly, however, although many species are shared between the eastern and western GSR, such as the dominant habitat-forming kelp *Ecklonia radiata* (Connell and Irving 2008; Marzinelli *et al.* 2015), these regions have been connected through the Bass Strait for only ~10 000 years (Waters 2008) and still have low genetic connectivity (Waters 2008; Coleman *et al.* 2013) and distinct biogeographical affinities (Waters *et al.* 2010).

The biological engine of the GSR are the kelp forests, which provide both the habitat and trophic foundation to support the system. Kelp forests are among the most productive ecosystems on the planet, with rates of productivity often exceeding that of the most intensively managed agricultural systems (Mann 1973). For example, the kelp forests of the GSR produce as much as 65 tonnes of biomass per hectare per year (de Bettignies *et al.* 2013), which is over 16 times more than Australia's most fertile wheat fields (http://www.ausgrain.com.au, accessed 3 December 2014). This biological powerhouse then feeds directly into coastal ecosystems as food and detritus (Bustamante and Branch 1996; Wernberg *et al.* 2006; Vanderklift and Wernberg 2010; Krumhansl and Scheibling 2012), critical for the energy and nutrient cycles supporting the rich marine life throughout the GSR and out into the wider ocean beyond shelf waters (Thompson *et al.* 2011). The high diversity and endemism of the GSR make it globally unique and intrinsically fascinating both aesthetically and scientifically. In addition, its sheer scale and close proximity to more than two-thirds of the Australian population (ABS 2001) means that the GSR forms an integral part of Australian culture and society. In turn, the GSR plays an important role in Australia's national economy, supporting a range of tourism ventures, and recreational and commercial fisheries.

Ecosystem services and the economics of the GSR

Ecosystem goods and services (herein referred to collectively as ecosystem services) are the direct (e.g. food production) or indirect (e.g. climate regulation, nutrient cycling, coastal protection) benefits that humans derive from ecosystems (Costanza et al. 1997). Quantifying the value of ecosystem services provided by the Great Southern Reef is critical as one measure of its importance to society, and to enable comparisons with other natural systems. Remarkably, analysis of 961 studies from a global database revealed that the value of ecosystem services provided by temperate reefs or kelp forest have scarcely been quantified for any region, let alone in Australia (Marine Ecosystem Services Partnership (MESP), see http://www.marineecosystemservices.org/, accessed 2 December 2014) (Fig. 2). As a result, major global and regional assessments of the value of ecosystem services do not recognise temperate reefs as distinct ecosystems but instead aggregate them with other shelf habitats (Costanza et al. 1997, 2014; de Groot *et al.* 2012). On the basis of these global assessments, the economic value of habitats that include temperate reefs is estimated at US$26 226–28 917 ha^{-1} $year^{-1}$ based on 2007 dollar values (de Groot *et al.* 2012; Costanza *et al.* 2014). These estimates inevitably misrepresent the value of temperate reefs for several reasons, not least of which is that without data on ecosystem services specifically provided by temperate reefs, their contribution cannot be included in the overall valuation. The profound implications of this are illustrated for coral reefs, where the estimated value of ecosystem services increased by a factor of 42 between 1997 and 2012, primarily due to new research on the value of coral reefs (Costanza *et al.* 2014). Similar valuations would likely apply to temperate reefs; however, currently there are insufficient studies to accurately estimate their value. For example, kelp forests are capable of rapid biomass accumulation and represent globally significant standing stocks of carbon. Information on the fraction that is sequestered into long-term carbon sinks such as marine sediments and deep ocean, thus contributing to climate change mitigation, is unknown (Laffoley and Grimsditch 2009). Harvesting and appropriate use of seaweeds from cultivated and wild sources (e.g. biofuels) could play a significant role in greenhouse gas mitigation (Chung *et al.* 2011), but does not factor into current valuations of temperate reef ecosystems. Similarly, the indirect positive effect of kelp forests enhancing fisheries (Bertocci *et al.* 2015) is unaccounted for.

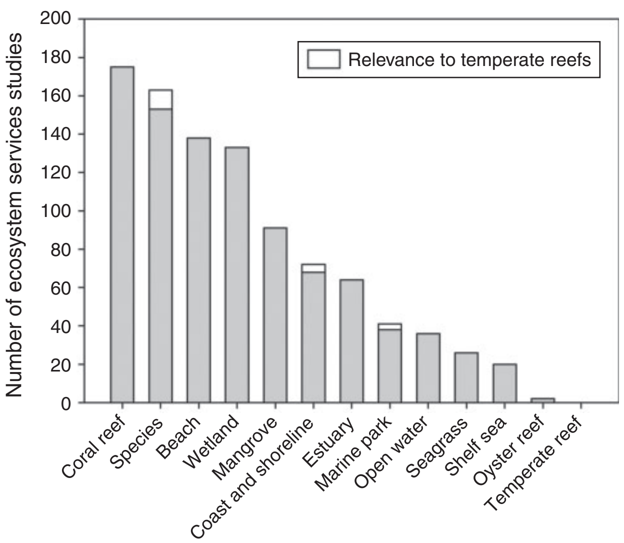

Fig. 2. The number of case studies on the value of ecosystem services from marine ecosystems worldwide. Open bars represent the number of studies within each category that are relevant to temperate reefs, despite not being the focus of the study. Just 17 of 961 studies in total were considered relevant to temperate reefs. Data provided by the Marine Ecosystem Services Partnership (MESP, see http://www.marineecosystemservices.org/).

Although they are conservative, existing estimates of the value of ecosystem services from temperate reefs highlight the important contribution that they make to human welfare, particularly for services that do not directly contribute to the economy. The value of seaweed and seagrass habitats estimated by Costanza *et al.* (1997) was almost entirely attributable to nutrient cycling within these ecosystems. On reefs shallower than 30 m where seaweed canopies dominate, the GSR covers $\sim 7.14 \times 10^6$ ha (Table 1), equating to as much as AU$187 billion $year^{-1}$ of nutrient cycling services that are critical to human welfare but currently do not feature in Australia's gross domestic product (GDP). Other more tangible ecosystem services that directly contribute to GDP, such as food production and recreation (e.g. tourism, fishing and surfing) are also missing from this valuation even if they make a significant contribution to the value of temperate reef ecosystems. Here we evaluate the ecosystem services provided by the GSR that directly contribute to the Australian economy and provide tens of thousands of jobs in industries such as commercial fishing, retail (e.g. surfing and fishing supply businesses), hospitality and tourism.

There are many commercial fisheries operating along the GSR. The two most valuable are the rock lobster and abalone fisheries, which together contribute ~AU$500 million $year^{-1}$ to the Australian economy (Table 1, Fig. 3). The Western Australian rock lobster fishery is the most valuable single-species fishery in the country and is worth ~AU$185 million $year^{-1}$ (Table S3). Similarly, wild-caught abalone in Tasmania alone are worth almost AU$100 million $year^{-1}$ (Table S3). By way of comparison, the combined gross value of commercial fisheries catches from the GBR region is ~AU$120 million $year^{-1}$ (Deloitte Access

Fig. 3. Economic importance of the Great Southern Reef (GSR). The Western Australian rock lobster (*Panulirus cygnus*, left picture) is Australia's largest single species fishery, worth AU$185 million $year^{-1}$. Wild-caught abalone, including blacklip ablone (*Haliotis rubra*, centre), contribute ~AU$140 million $year^{-1}$ to Australia's economy before processing. Recreational activities (right), such as diving, fishing and surfing, on the GSR attract millions of participants every year and inject tens of millions of dollars into regional coastal economies. Rock lobster photograph © J. Costa 2013 (reproduced with permission); abalone and recreation photographs © S. Bennett.

Economics 2013), less than one-quarter of the value of rock lobster and abalone on the GSR. Standardised by area, rock lobster and abalone fishing on the GSR is more than seven times more valuable than all commercial fishing on the GBR combined.

The value of tourism directly associated with the GSR has not been measured for any local or regional sections of reef, as far as we are aware. Nevertheless, total tourism expenditure in coastal municipalities immediately adjacent to the GSR provides an approximate indication of its value. Tourism along the GSR represents a multibillion dollar industry (AU\$38 billion year^{-1}, based on 2007–08 figures: Tables 1, S4) (Tourism Research Australia 2011) and is particularly vital to regional economies along the GSR. Of course, not all tourism expenditure can be directly attributed to the GSR and these figures inevitably overestimate direct, reef-related values, particularly in major cities where tourists are attracted for many reasons. Nevertheless, in regional coastal communities alone (i.e. excluding the cities of Sydney, Newcastle, Wollongong, Melbourne, Adelaide and Perth), where reef-related tourism such as fishing, scuba-diving, surfing 'reef breaks', whale watching and other ecotourism ventures are a major drawcard, total tourism expenditure is estimated at ~AU\$9.8 billion year^{-1}, representing ~15% of the total economic activity in some regional areas (e.g. Philip Island = 18.7%, Tasmanian west coast = 16.2%, Kangaroo Island and Tasmanian east coast = 14%: Tourism Research Australia 2011). The GSR is therefore a major contributor to the socio-economic fabric of Australia and particularly that of regional coastal communities (Metcalf *et al.* 2014).

Recreational activities on the GSR are similarly large, primarily due to the spatial scale and concentration of population centres along its shores. Approximately 67% of the Australian population live within 50 km of the GSR (ABS 2001), which if scaled to Australia's 2014 population, equates to 15.9 million people. Of those, it is estimated that ~5.3 million regularly participate in recreational fishing. On the basis of 2001 values, recreational fishing along the GSR is estimated to be worth ~AU\$500 million year^{-1}, with over 6 million person-fishing-days conducted each year (Tables 1, S5). Nationally, coastal-water fishing effort is the highest among all waterbody-types (41%), with 9.5 million fishing events per year, compared with 35% in estuaries, 11% in rivers, 8% in lakes and dams, and 4% offshore (Henry and Lyle 2003). Owing to their size, the highest numbers of recreational fishers in Australia are concentrated adjacent to the major cities of Sydney, Melbourne and Perth, which are also experiencing the highest rates of population growth in the nation. Therefore, although more recent participation rates are not available, the economic value of recreational fishing on the GSR will inevitably have grown over the past decade. The economic value of other forms of recreation on the GSR is difficult to quantify; however, a range of other activities take advantage of the wild natural beauty, pristine waters and healthy ecosystems of the GSR even if not directly associated with its kelp forests. For example, most of the estimated 2.7 million surfers in Australia (www.surfingaustralia.com.au) live adjacent to the GSR. Much of the recreation and tourism in iconic places such as Phillip Island and Torquay in Victoria, or Margaret River in Western Australia, are based around surfing 'reef breaks' that form on the GSR and attract millions of visitors each year (Tourism Research Australia 2011).

Public perception and research investment

Despite its intrinsic and economic value, public perceptions of the Great Southern Reef are low compared with other comparable natural assets in Australia such as the GBR. Similarly, or perhaps as a consequence, rates of research investment into understanding the ecology that underpins the GSR ecosystem are also low.

Quantifying perceptions of the GSR by the Australian public is challenging. We use news reports as a proxy for public awareness but acknowledge that the relationship between news reports and public awareness is not necessarily a simple one (Duarte *et al.* 2008). We searched the online archives of 15 major news outlets from across Australia (Table S6) to investigate the public awareness of temperate reefs, and we compared this to coral reefs, the most comparable major ecosystem in Australia. Following the methods of Duarte *et al.* (2008), the electronic archives were searched during November 2014 to compare the number of news hits for (1) 'temperate reef' and 'coral reef', and (2) 'kelp' and 'coral'. The electronic archives all covered at least two years but did not all cover the same period. Therefore a rigorous analysis of temporal trends in reporting on the different ecosystems was not possible.

The media search revealed that for both comparisons (kelp *v.* coral and temperate reef *v.* coral reef), news reporting was more than an order of magnitude higher for coral reefs than for temperate reefs (Table S6). 'Kelp' accounted for 2.9% $\pm$ 0.6 (mean $\pm$ s.e.) of the total number of news reports on 'kelp' and 'coral' in Australian media. Similarly 'temperate reefs' accounted for only 5.6% $\pm$ 1.8 (mean $\pm$ s.e.) of all media reports on 'temperate reef' and 'coral reef'. This finding was consistent irrespective of the geographical location of the media outlet. That is, despite their target audiences living thousands of kilometres away from the nearest coral reef, and immediately adjacent to the GSR, 81–99% of all reef-related stories reported in Tasmanian, Victorian and South Australian newspapers focused on coral or coral reefs.

To ascertain any patterns in public investment in research funding we searched the funding outcomes of all major funding schemes announced by the Australian Research Council since 2010 (project codes DP10, LP10 etc.) (http://www.arc.gov.au/applicants/fundingoutcomes.htm, accessed 29 March 2015) for all projects in ecology (FoR code 0602) as well as projects returned using the search words 'coral' and 'kelp'. From the project description it was ascertained whether the project had a coral reef or temperate reef focus. This approach focused the search on the major habitat-formers (corals and kelps) but did not exclude other groups of organisms (e.g. barnacles, fish, anemones) or distinguish between subtidal and intertidal habitats.

The imbalance in news reporting was also reflected in public investment in research funding within Australia, a pattern seen across all major funding schemes. Over the past five years (2010–14), coral reefs received AU\$55.3 million in total research funding from the Australian Research Council, compared with only AU\$4.0 million allocated to temperate reef research (Fig. 4). Australia is a world leader in coral reef research, reflecting decades of investment and the recognition of the importance of coral reef systems. The social, ecological and economic importance of kelp forests in Australia justifies a similar

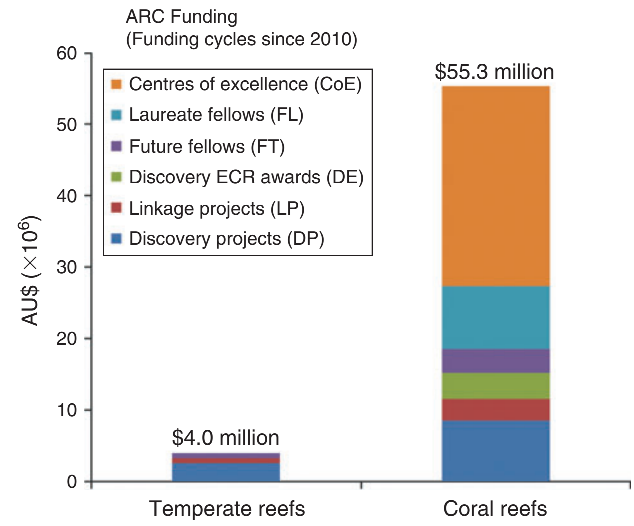

Fig. 4. Public research spending on temperate and coral reef research awarded by the Australian Research Council (ARC) between 2010 and 2015 (DP10–DP15, LP10–LP14, DE12–DE15, FT10–FT14, FL10–FL14, CoE 2014).

commitment to temperate reefs. The current funding imbalance creates a research vacuum on the GSR, and undermines the continued development of sustainable industries and knowledge-based management of the region.

Status and threats

Like many of Australia's natural assets, the Great Southern Reef is relatively healthy and well managed by global standards. However, with growing pressures from climate change, population growth and coastal urban development, the GSR is at increasing risk, with many areas already showing severe signs of stress and degradation (Connell *et al.* 2008; Department of Sustainability, Environment, Water, Population and Communities 2011; Johnson *et al.* 2011; Wernberg *et al.* 2011*b*). Warming is currently occurring 2–4 times the global average in the western and south-eastern GSR respectively (Pearce and Feng 2007; Ridgway 2007; Hobday and Pecl 2014). Warming in the south-eastern GSR has been largely due to increased frequency and size of eddies of the East Australian Current propagating poleward towards Tasmania (Johnson *et al.* 2011). The increased influence of warm nutrient-poor water from the East Australian Current in eastern Tasmania has been associated with dramatic losses of giant kelp (*Macrocystis pyrifera*) forests (Johnson *et al.* 2011). As a consequence, in August 2012 the Australian giant kelp forests became the first marine community to be listed as endangered under the *Environment Protection and Biodiversity Conservation Act* (http://www.environment.gov.au/resource/giant-kelp-marine-forests-south-east-australia, accessed 4 June 2015). In 2011, gradual warming on the western GSR was punctuated by an unprecedented marine heatwave that saw summer temperatures reach 2–6°C above long-term maxima across almost 2000 km of coastline (Pearce and Feng 2013; Wernberg *et al.* 2013*b*). The marine heatwave had catastrophic impacts on the western GSR, resulting in a dramatic loss of kelp forests across more than 960 000 ha of reef in the north-western GSR (T. Wernberg and S. Bennett, unpub. data) and >100 km range contraction of other dominant canopy-forming seaweeds (Smale and Wernberg 2013). Range contractions present a serious risk of species extinction on the GSR because of the combination of lack of suitable habitat for retreat farther south and high rates of endemism (e.g. Wernberg *et al.* 2011*a*). In addition to range contractions and habitat losses, warming is also facilitating the addition of new species as warm temperate and tropical species increase in abundance and expand their ranges poleward (i.e. tropicalisation) into previously cooler environments (Wernberg *et al.* 2013*b*; Vergés *et al.* 2014; Bennett *et al.* 2015*a*). Observed changes include expansion of a subtidal sea urchin (Ling *et al.* 2009), a range of intertidal invertebrates (Pitt *et al.* 2010), zooplankton (Johnson *et al.* 2011), and coastal fishes (Johnson *et al.* 2011; Last *et al.* 2011; Bennett *et al.* 2015*a*; Robinson *et al.* 2015). In the case of the sea urchin (*Centrostephanus rodgersii*) in the south-eastern GSR, range extension and population expansion has led to overgrazing of kelp forests, resulting in barren formation and reduced fisheries productivity (Johnson *et al.* 2011). Similarly, in the south-western GSR tropical herbivorous fishes are now preventing the recovery of kelp forests lost during the 2011 marine heat wave (Bennett *et al.* 2015*a*).

Local stressors are also having an important impact on the health of the GSR. Kelp forests on the eastern (Coleman *et al.* 2008) and central (Connell *et al.* 2008) GSR have undergone decline and loss adjacent to intense coastal development as a result of localised pollution including nitrogen enrichment from discharge of sewage and storm water (Gorman *et al.* 2009). Such losses are likely to increase over the next century as the human population increases along the GSR, and as local declines accumulate they eventually coalesce to manifest as regional impacts. Furthermore, there are synergistic impacts between local nitrogen enrichment and global enrichment of carbon dioxide (i.e. ocean acidification: Connell *et al.* 2013) that causes a switch in the competitive dominance between perennial kelp and opportunistic seaweed turfs (Connell *et al.* 2014), favouring the establishment of resilient turf-dominated habitats. Not all areas of the GSR will suffer kelp loss because of the inherent stabilising processes of ecosystems (Bennett and Wernberg 2014; Bennett *et al.* 2015*b*; Connell and Ghedini 2015) that compensate for increasing effects of multiple disturbances (Ghedini *et al.* 2015) and broad spatial variation in the importance of particular or multiple stressors (Wernberg *et al.* 2011*b*). Because impacts ultimately depend on interactions between global and local stressors that might vary from place to place both in nature and in strength (e.g. Wernberg *et al.* 2010; Bennett and Wernberg 2014; Bennett *et al.* 2015*b*), understanding the current and future threats faced by the GSR from a local to continental scale is essential to enable appropriate management of the system and ensure the sustainability of the intrinsic value and ecosystem services derived from it (Connell and Irving 2009; Wernberg *et al.* 2011*b*).

Management of the GSR in a rapidly changing environment

The fastest rates of population growth in Australia are adjacent to the Great Southern Reef, and the current 16 million people within 50 km of the coast is projected to increase by another

3 million in the next decade and double in size by 2060 (based on a median growth rate 1.6%: Pink 2013). Given the associated increases in urbanisation and coastal development, maintaining and enhancing the social–ecological resilience of the GSR will be difficult in some regions, and losses of some GSR habitats are inevitable. The additional pressures from ongoing climate change will result in a range of existing and novel challenges for management of temperate reefs and associated industries along the southern coast of Australia. Importantly, management of local conditions can alleviate, if not reverse, global stressors (Wernberg *et al.* 2011*b*; Falkenberg *et al.* 2013) and there is substantial local impetus for participation in addressing the problems. For example, a study from South Australia found that households in the immediate area of marine habitat loss were willing to pay up to AU$67.1 million for improvements to waste-water management to reduce impacts (MacDonald *et al.* 2015).

Increased recognition of ecological linkages across southern Australia and the GSR as an entity will strengthen the potential for cooperative management among the federal and state governments. As a starting point, greater understanding of the functioning of the GSR entity will be required, with new 'big picture' research focusing on linkages and contrasts across the GSR system. Consistent governance through spatially flexible approaches will likely provide the most ecologically sensible and cost-effective management strategies. For example, currently variable fisheries regulations both within and among states (e.g. licensing, gear restrictions, seasonal closures and bag limits) may need to be harmonised for highly mobile and widespread species whereas locally appropriate management targets (e.g. nitrogen loads: Gorman *et al.* 2009) will be required where regional differences in, for example, sensitivity to water pollution and fishing are recognised (Connell 2007). Novel industries that exploit the GSR may arise, including bioprospecting for, and harvesting of, unique seaweed and sponge species, which will require new or cooperative legislation. Recall that our forbearers effectively fished-out native oyster reefs before the formation of the Australian parliament, representing the wholesale loss of thousands of kilometres of temperate habitat needed to maintain fish production and water quality (Alleway and Connell 2015). By recognising the GSR as a holistic and connected system, piecemeal decision-making can be avoided, and the importance of integrated planning and cumulative risk recognised, such that Australia's temperate reefs continue to support and deliver valuable socio-economic and ecological services into the future.

Conclusions

There is currently a paradoxical (and concerning) mismatch between the low public awareness and investment in Australia's temperate reef ecosystem and its high ecological and economic value for Australian society. By recognising the 'Great Southern Reef' as an entity and defining the benefits derived from it as a whole, we have highlighted the profound importance of this system. This process is only a first step towards a broader discussion about, and greater scrutiny of, the values of the GSR that will engender relationships and perceptions of Australian society towards this system. Given the rapid historical rates of environmental change throughout temperate Australia (Lough and Hobday 2011) and projected changes (Hobday and Lough 2011; Oliver *et al.* 2014), sustainable and adaptive management of the GSR over the coming decades will require a strong knowledge-base and generation of a public and political will to look after the system, and a commitment that reflects the immense ecological social and economic benefits we derive from the Great Southern Reef.

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