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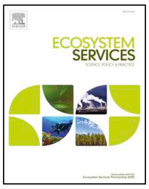

Communicating the value of marine conservation using an ecosystem service matrix approach

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ABSTRACT

Matrix approaches are useful for linking ecosystem services to habitats that underpin their delivery. Matrix applications in marine ecosystem services research have been primarily qualitative, focusing on 'habitat presence' without including other attributes that effect service potential. We developed an evidence-based matrix approach of Ecosystem Service Potential (ESP) for New Zealand benthic marine habitats, and used two marine reserves to demonstrate that integrating information on the spatial extent and quality of habitats improved ESP evaluation. The two case studies identified substantial spatio-temporal variability in ESP: within one reserve, specific ESP showed an approximately 1.5-fold increase in the 29 years following protection. A comparison of two reserves found that the spatial extent of habitats contributing to the medicinal resources and waste-water treatment were 5 and 53 times greater respectively in one relative to the other. Integrating habitat area and quality with the ESP matrix improves on previous marine matrix-based approaches, providing a better indication of service potential. The matrix approach helps to communicate the non-market value of supporting and regulating services and can be used by resource managers to identify and track the potential for benefits derived from benthic marine habitats within existing, or new, marine protected areas.

1. Introduction

Ecosystem services (ES) have become an established concept for articulating the benefits that people derive from ecosystems (Gómez-Baggethun et al., 2010), and many countries now have national and international statutory commitments to protect elements of the natural environment from which ES flow (e.g., Aichi Target 11; http://www.cbd.int). Patterns of societal demand for and perceived benefits of ES are known to vary over time, which can muddle efforts to measure and map ES. Consequently, marine protection should consider the potential of habitats to provide ecosystem services (Ecosystem Service Potential, ESP) as well as the benefits currently being realised, or demanded by, society. For example, a century ago the provision of food was recognized as the primary value of the marine environment with few people anticipating the need for services such as carbon sequestration (because of growing concerns about climate change) and nutrient removal (due to increased loadings associated with altered land use). Conservation planning should focus on protecting ecosystem processes, structures or functions that underpin a representative range of ESP's, rather than exclusively focussing on those ES related to current usage. For MPAs to be successful and accepted, a balance between managing short-term needs and longer-term service resilience is required. To achieve this, marine conservation requires spatial tools that can better link the quality and spatial extent of protected habitats to ESP.

'Matrix' approaches have been used successfully in terrestrial systems to link ecosystem services to the habitats and ecosystem processes that underpin service generation (Burkhard et al., 2009, 2014). ESP matrices function by arranging services into columns and habitats into

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Table 1
Descriptions of ecosystem services incorporated in the ecosystem service matrix, based on TEEB and CICES ecosystem service classifications.

Service category	Ecosystem service	Service description
Habitat & supporting services	Primary production[1]	The activity of plants, algae and microbes using solar radiation to create organic compounds from inorganic constituents. This important source of energy underpins most marine food-webs and ecosystems
	Nutrient regeneration[2]	The breakdown and conversion of organic matter into inorganic nutrients by the activities of marine species. Sediments are often the most active area for organic matter remineralisation, but this process also takes place in the water column
	Habitats for species	Marine species, through their physical structures or activities, provide important living spaces for other organisms (Holt et al., 1998)
	Sediment formation and composition	Marine organisms play a role in the provision of sediment. Over time, carbonates derived from structures such as mollusc shells and coccolithophores form sediments. Silicate from planktonic diatom deposition can dominate in other areas
Regulating services	Carbon sequestration and storage	Marine habitats and species influence the production and storage of carbon dioxide and regulation of the carbon cycle. CO_2 is absorbed by the oceans and used by taxa such as macrophytes, molluscs, crustacea and brachiopods in tissue or shell material (Libes, 1992)
	Erosion prevention	This is the role of biota in retaining sediment. When in sufficient densities, biota prevent erosion of sediments and increase deposition (Thrush et al., 1996; Lelieveld et al., 2004)
	Local climate and air quality	Marine habitats and their biota play a role in regulating the gaseous composition of water masses and exchanges with the atmosphere (Thurman and Trujillo, 2003; Boyd et al., 2004) e.g. supply and removal of volatile organic halides, greenhouse gases
	Waste-water treatment	Marine organisms are able to mitigate the possible impacts of contaminants through burial or binding in tissue, or altering them so that their toxicity is reduced (e.g., biotransformation) (Beaumont et al., 2007)
	Moderation of extreme events	Marine habitats and biogenic structures can mitigate environmental disturbances from storm surges and wave action (Danielsen et al., 2005). Habitat structures modify flow, dissipate energy and reduce erosion which protects coastal infrastructure (Fonseca and Cahallan, 1992). This definition considers meteorological events/ tidal process, but excludes Tsunami
Provisioning services	Food	Marine ecosystems contain species that can be extracted for human consumption
	Raw materials	Marine ecosystems contain renewable material that can be extracted for purposes other than human consumption (i.e., fishmeal, fertilizers, fibres, shell-hash, ornaments etc)
	Medicinal resources	Marine organisms can contain genetic information and biogenic chemicals that have uses in medical and pharmaceutical industries (Sipkema et al., 2005)

[1] Neither TEEB or CICES explicitly include primary production, which is an ‘intermediate’ service and a prerequisite of other ‘final’ services (Haines-Young and Potschin, 2010). From a management perspective, primary production is an important service to consider.

[2] ‘Nutrient regeneration’ processes are considered in the CICES, but are referred to as the ‘chemical condition of salt waters’ within the ‘water conditions’ group and the ‘decomposition and fixing processes’ class within the ‘Soil formation and composition’ group. For simplicity, nutrient regeneration is used here.

rows, with a habitat’s potential to contribute to the provisioning of a specific service located at their intersection (Jacobs et al., 2014). The resulting matrix can be read horizontally to observe the mix of services that a habitat potentially contributes to, or vertically to identify which habitats potentially contribute to a specific ES. The major advantages are that matrices can function with gaps in information, can be iteratively improved over time, are technically simple, and can utilise a range of information from empirical data through to expert opinion or local knowledge (Burkhard et al., 2009; Jacobs et al., 2014). However, variability in the quality of underpinning information and uncertainty are not always transparent when matrices are applied and interpreted.

Although the development and spatial application of ESP matrices has been problematic in marine systems (due to poorly-defined linkages between habitats, ecosystem processes and ESP, high connectivity of marine environments, and limited high-resolution biophysical information at large spatial scales), they remain a promising tool for protecting valued ES in the marine environment. Potts et al. (2014) developed an ESP matrix for the UK and assessed a variety of marine habitats and species for their potential contribution to 25 services. They then applied the matrix to five case-study marine protected areas (MPAs) using habitat presence to identify ESP. Although this was a major advance, Potts et al. did not include either habitat area or habitat quality in their analysis, factors that are known to influence the magnitude and extent of ESP (Luck et al., 2003). Although ecosystem services do not always scale linearly with habitat size (Barbier et al., 2008; Koch et al., 2009), consideration of area is important because the spatial extent of habitats is a principal determinant of the magnitude of ESP (Harrison et al., 2014). Similarly, destruction of habitat is a major driver of the loss of ESP (Hoekstra et al., 2005; Polasky et al., 2011; Costanza et al., 2014). For example, estuarine mangroves are estimated to cover between 13.8 and 15.2 million hectares globally, but this habitat is being lost at a rate of 0.7–3% annually (Pendleton et al., 2012) with concomitant changes in global potential CO_2 emissions of $7.0\,\mathrm{Tg\,CO_2e\,yr^{-1}}$ (Atwood et al., 2017). Similarly, changes in habitat quality often coincide with changes in the physical, chemical and biological features of an ecosystem. As habitat quality changes, so do the processes that regulate ESP (Mace et al., 2012), and decline in habitat quality has been linked to the deterioration and loss of multiple ES (Raffaelli and Frid, 2010; Dobson et al., 2006; Haines-Young and Potschin, 2010; Gonzalez et al., 2011; Nagendra et al., 2015).

International obligations such as the United Nations’ Convention on Biological Diversity (CBD) Aichi Target 11 (http://www.cbd.int) require that ES are conserved through effectively managed protected areas (SCBD, 2010). As a signatory to the CBD, New Zealand is committed to establishing marine protected areas (MPAs) to protect biodiversity and ES. However, there is currently a lack of robust spatial tools to facilitate the evaluation of ESP in existing MPAs, and little consideration of ESP when evaluating sites for new MPA’s. To help address this shortfall we (i) developed an evidence-based ESP matrix for New Zealand benthic marine habitats; and (ii) extended the methods of Potts et al. (2014) by using New Zealand MPA case-studies to demonstrate how a matrix can be combined with information on the spatial extent and quality of benthic marine habitats to better evaluate ESP.

2. Methods

We developed a matrix to identify linkages between ESP and nationally common and iconic benthic marine habitats in New Zealand and subjected it to peer review through an expert-based process. We then applied the matrix to two case studies; the first evaluating changes in ESP over a 29-year period following the establishment of a fully no-take MPA, and the second integrating habitat extent and quality in

Table 2
The relative importance of habitats to Ecosystem Service Potential (ESP). Cell shading indicates the relative contribution to ES potential, with roman numerals specifying the supporting evidence. Scoring assumes that habitats are in a good state of health. The matrix can be read horizontally to observe the mix of ES that a habitat contributes to, or vertically to identify which habitats contribute to a specific ES. Cells with diagonal lines indicate that they could not be assessed due to lack of available literature and expert knowledge.

	Habitat & supporting services				Regulating services					Provisioning services		
Habitats	Primary production	Nutrient regeneration	Habitats for species	Sediment formation & composition	Carbon sequestration & storage	Erosion prevention	Local climate and air quality	Waste-water treatment	Moderation of extreme events	Food	Raw materials	Medicinal resources
Black coral garden	iii	░ i	■ iv	i	i	i	i	⧄	i	i	iii	░ ii
Brachiopod bed	i	░ i	░ ii	░ iv	░ iv	░ i	░ i	░ i	i	iv	i	i
Bryozoan bed	i	░ i	■ iv	▩ iv	▩ iv	░ i	░ i	⧄	i	i	i	▩ ii
Bull kelp (*Durvillaea*) forest	■ iv	i	▩ iv	iv	▩ i	ii	▩ i	ii	i	ii	■ iv	░ ii
Cerianthid bed	i	░ i	■ ii	i	i	i	i	░ ii	i	i	i	░ ii
Cockle bed	░ iv	■ iv	▩ iv	■ i	■ i	▩ i	░ i	■ iii	i	■ iii	▩ i	⧄
Coralline paint	░ ii	i	░ iv	░ iv	░ iv	i	░ i	i	i	i	i	░ ii
Coralline turfing algae	░ ii	i	▩ iv	░ iv	░ iv	░ i	░ i	i	i	i	i	iii
Deep/cold coral garden	ii	░ i	■ iv	░ iv	■ iii	i	░ i	░ i	i	i	iii	░ ii
Ecklonia forest	■ iii	i	■ ii	⧄	■ ii	░ i	■ ii	░ iv	i	░ iii	▩ i	░ iv
Erect soft sediment inverts	i	▩ i	■ iii	i	░ i	░ i	i	⧄	i	i	░ i	░ i
Green algal forest	■ i	i	▩ i	i	i	░ i	▩ i	i	i	░ ii	░ i	░ ii
Heart urchin plain	░ iv	■ iv	⧄	i	░ ii	i	░ iv	░ ii	i	i	i	i
Horse mussel bed	iv	■ iv	■ iv	■ i	░ i	■ iv	░ i	⧄	i	░ i	⧄	i
Macrocystis forest	■ ii	i	■ ii	⧄	■ ii	░ i	■ ii	░ iv	i	░ iv	■ ii	░ iv
Mangrove forest	■ iv	■ ii	▩ iv	▩ iv	■ iv	■ iv	■ iv	▩ ii	■ iii	i	i	⧄
Mixed brown algae	■ i	i	■ iv	i	░ i	░ i	▩ i	░ iv	i	░ iv	▩ iv	▩ iv
Mixed suspension feeders	i	▩ iv	▩ i	i	i	i	░ i	░ i	i	░ i	░ i	⧄
Mobile rocky invertebrates	i	i	░ i	░ i	▩ i	i	░ i	i	i	i	░ i	⧄
Mud crab bed	i	■ iv	░ i	⧄	ii	▩ iv	⧄	░ iv	i	i	⧄	⧄
Mussel bed	i	▩ i	■ iii	░ i	■ i	▩ i	░ i	■ i	i	▩ iv	▩ iv	■ iv
Oyster reef	i	■ ii	■ ii	▩ iv	■ ii	■ ii	░ i	■ ii	i	■ iii	░ ii	░ ii
Paua bed	i	░ ii	░ i	░ i	■ ii	i	░ i	ii	i	■ iv	■ iii	i
Red algae meadow	▩ iv	i	■ iv	i	░ i	░ i	▩ i	░ ii	i	░ iv	■ iv	▩ iv
Red coral garden	i	░ i	▩ i	░ iv	▩ i	i	░ i	⧄	i	i	i	⧄
Rhodolith bed	░ ii	i	■ iii	░ iv	■ iii	░ i	▩ ii	i	i	i	i	░ iii
Saltmarsh	■ ii	■ ii	░ ii	▩ ii	■ ii	■ ii	■ ii	■ ii	■ ii	i	i	⧄
Scallop bed	i	░ i	░ i	■ i	■ ii	i	░ i	⧄	i	■ iv	░ i	⧄
Seagrass meadow	■ iv	■ ii	■ ii	⧄	■ iv	■ ii	■ iv	■ i	i	i	⧄	⧄
Seapen bed	i	░ i	▩ ii	⧄	░ ii	i	⧄	⧄	i	i	i	░ ii
Soft sediment burrow communities	i	■ iv	░ iv	░ i	i	▩ iii	░ i	▩ iii	i	i	i	⧄
Soft sediment whelks assoc.	i	░ i	⧄	⧄	▩ iv	i	⧄	⧄	i	░ iii	░ iii	⧄
Sponge garden	ii	░ iv	■ iv	░ iv	iv	░ i	░ i	■ iv	i	i	░ iv	▩ iv
Surf clam bed	i	▩ i	░ i	■ i	■ i	▩ i	░ i	⧄	i	■ iii	⧄	⧄
Tubeworm mat	i	▩ ii	▩ i	⧄	i	■ ii	⧄	⧄	i	i	i	i
Tubeworm reef	i	░ i	■ iv	▩ iv	■ iv	░ i	░ i	░ i	i	i	i	ii
Urchin plain	i	░ ii	░ i	░ iv	░ iv	i	░ i	i	i	▩ iv	░ i	i
Wedge shell bed	i	■ iv	⧄	■ i	▩ i	i	░ i	⧄	i	i	i	i

Contribution to Ecosystem Services		**Confidence in score**	
■	Significant contribution	iv	New Zealand focused, peer-reviewed literature
▩	Moderate contribution	iii	New Zealand focused, grey literature
░	Low contribution	ii	Overseas literature
	No or negligible contribution	i	Expert opinion
⧄	Not assessed	⧄	Not assessed

comparisons of ESP between two marine reserves.

2.1. Ecosystem service matrix for New Zealand's benthic marine habitats

We constructed an ESP matrix that incorporated 12 services (as columns) that were divided into three broad categories: Habitat and supporting services; Regulating services; and Provisioning services. Services were based predominately on The Economics of Ecosystems and Biodiversity classification (TEEB, 2010), with the addition of primary production and nutrient regeneration as important 'intermediate' services, and the addition of 'sediment formation and composition' from the Common International Classification of Ecosystem Services CICES classification (Haines-Young and Potschin, 2013) (Table 1). Cultural services were excluded because they can differ between generations, ethnicities, religions, countries of origin, income level, location of residence and sector of society (Hofstede, 1991; Hebel, 1999), and should be considered at multiple spatial scales to reflect 'layers of culture' rather than at the national scale at which our matrix is constructed. The matrix included 38 benthic marine habitats as rows, incorporating nationally common and iconic fauna and flora, from 0 m (Mean High Water Springs) to 200 m depth across soft sediments and rocky strata (Table 2).

In considering the contribution of habitats to ESP, we focused on emergent properties rather than just the direct contribution of the defining species itself. Emergent properties are an important inclusion because not considering them can lead to a failure to capture a full suite of services. For example, the bivalve shellfish species *Austrovenus stutchburyi* (New Zealand cockle) is not a primary producer, but beds of this species typically have higher rates of primary production than similar habitats absent of them (Jones et al., 2011). When ranking the contribution of habitats to ESP, we assumed that they are in a good state of health as assessment of habitat quality is incorporated into our approach during site-specific assessments.

To score the matrix, we shaded cells within the matrix to indicate the relative importance of each habitat to ESP (low, moderate, significant: Table 2). We used the best available information (see SI Table 1), which included: New Zealand-focused peer-reviewed scientific literature that verified a service score; support from non-peer-reviewed scientific literature with a New Zealand focus; peer-reviewed literature external to New Zealand; and expert opinion. We used roman numerals within the matrix to demonstrate confidence in the assessment (i–iv, Table 2). Some cells could not be scored due to a lack of available literature and expert knowledge. Matrix scoring was reviewed and revised following feedback from an expert workshop attended by 18 marine scientists (May 12th, 2014, Auckland). A diverse set of participants were invited based on disciplinary and subject matter expertise, and their track records of publishing significant science in international journals. The workshop Chair moderated a discussion reviewing the list of services and habitats, the availability of published literature to support scoring, scoring of the matrix via expert opinion in the absence of published literature, and the identification of knowledge gaps. Following the workshop, an extensive editing process was carried out and a revised matrix was emailed to participants for a final round of review.

2.2. Case study 1: changes in ecosystem service potential over time

Case study 1 evaluated temporal changes in ESP within New Zealand's first fully no-take MPA, the Cape Rodney-Okakari Point Marine Reserve in north-eastern New Zealand (Fig. 1). The reserve was established in 1975 for the purpose of scientific research and the maintenance of biodiversity. Disturbance or removal of marine life and materials within the reserve, including fishing of any kind, is strictly prohibited. The reserve is ~547 ha in extent, was originally mapped in 1977 (Ayling, 1978, 1981) and was remapped in 2006 by Leleu et al. (2012) who quantified changes in the spatial extent of benthic habitats following 29 years of protection. The area of kelp forest within the reserve in 2006 had more than doubled in size relative to 1977, with concomitant declines in the extent of urchin plains and crustose coralline habitat (Leleu et al., 2012; Fig. 2). The spatial extent of mixed algae and algal turf increased slightly, while that of sponge garden, deep reef and sediment was stable (Fig. 2). We assessed ESP for each of the 1977 and 2006 habitat maps as presented in Remy-Zephir et al. (2012), and calculated proportional change in ESP over the interim 29-year period. As metrics of habitat quality were unavailable for the 1977 habitat data habitat quality was not included in this case study.

2.3. Case study 2: integrating habitat quality and area in the evaluation of ecosystem service potential

Case study 2 integrated metrics of benthic habitat area and habitat quality in an evaluation of the differences in ESP provided by the Cape Rodney-Okakari Point Marine Reserve and the Whanganui A Hei Marine Reserve (Fig. 1). The Whanganui A Hei Marine Reserve was established in 1992 on the east coast of the Coromandel Peninsula with the purpose of preserving for the purposes of scientific study, habitats that are representative of the open mainland. Within the reserve, the disturbance or removal of marine life and materials, including all fishing of any kind, is prohibited. The reserve is ~840 ha in extent and was mapped most recently in 2013 (Haggitt, 2017), with seven biological habitat types classified: soft sediment whelk association, sponge garden, coralline turfing algae, *Ecklonia radiata*, *E. radiata* with sponge, mixed brown algae and soft sediment burrow communities (Fig. 3). For this analysis, we combined '*E. radiata*' and '*E. radiata* with sponge' into a single '*Ecklonia* forest' habitat type.

Robust measures of benthic habitat quality require a thorough description of a range of interdependent attributes that include biomass, density, health, the diversity of component species, the degree of fragmentation and connectivity of habitat patches, and the levels of anthropogenic stressors (Diaz et al., 2004). In lieu of all types of information being available, we used data from 3772 1 m^{-2} quadrats sampled by Shears & Babcock (2007) at 205 sites across New Zealand to calculate the mean and 95% confidence interval for the combined biomass or density of the defining species for each habitat (see Table 3; for a full description of the sampling sites and methods see Shears and Babcock, 2007). We used the lower and upper bands of the 95% confidence intervals as thresholds for low and high habitat quality, respectively (Table 3). Using the same dataset, we then determined the proportion of quadrats sampled within each habitat type within each reserve (Cape Rodney-Okakari Point or Whanganui A Hei) that exceeded the low or high habitat quality thresholds, and used these proportions to calculate the overall area of each habitat type that was of either low, medium or high quality. For example, we used a high-quality threshold of 323.9 g m^{-2} for *Ecklonia* forest; at the Whanganui A Hei Marine Reserve there was 120 ha of *Ecklonia* forest with 46% of the 76 quadrats sampled within *Ecklonia* habitat exceeding the high-quality threshold; therefore, we calculated the area of high quality *Ecklonia* habitat as 120 ha × 0.46 = 55 ha. There was no information from the Shears & Babcock (2007) dataset on the biomass or density of the defining species for the mixed suspension feeders or soft sediment burrow community habitats. Given the exclusion of fishing methods such as trawling and dredging in marine reserves, which can reduce the density, size and structural complexity of suspension feeders and burrow communities, we considered it unlikely that these habitats would be of low quality. Further, given a lack of evidence that these habitats were of high quality, we gave them a medium quality score.

Because there are inconsistencies in habitat mapping methodologies between years and marine reserves and our estimates of habitat quality are not direct measures, the analyses presented below should be understood as using the best available data of sufficient quality and scale to allow the robust demonstration of our approach.

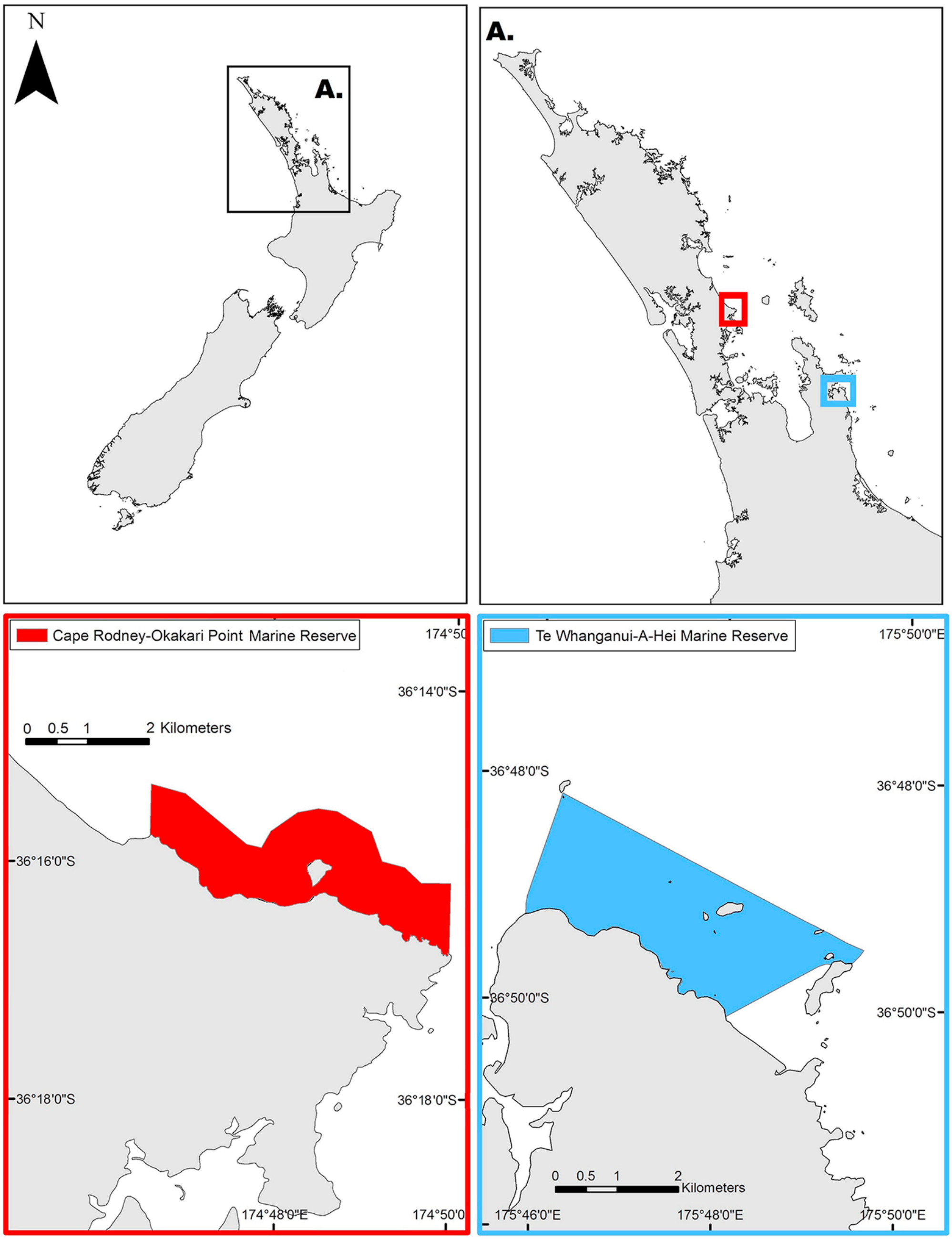

Fig. 1. Map of the Hauraki Gulf, north-eastern New Zealand (A), indicating the location of the study areas at the Cape Rodney-Okakari Point Marine Reserve (red polygon, ~547 ha in extent) and the Whanganui A Hei Marine Reserve (blue polygon, ~840 ha in extent). Latitude and longitude in Degrees-Minutes-Seconds.

2.4. Assessment of ES potential within the case-study areas

For each of the case studies, we calculated the area contributing to ESP (*aESP*) as:

$$\mathrm{a}ESP_{ijk} = \sum_{h=1}^{n} a_{ijk} \tag{1}$$

where h is habitat type, a is habitat area, i is the service, j is the contribution to ESP (significant or moderate) and k is habitat quality (low, medium, high; this term was omitted from case study 1 where data on habitat quality was unavailable). This allows reporting on the distribution of area amongst services, contribution, and habitat quality groupings.

For case study 1, we calculated proportional change in $aESP_{ij}$ between 1977 and 2006 as:

$$\Delta aESP_{ij} = \frac{aESP_{ij}^{2006}}{aESP_{ij}^{1977}} - 1 \tag{2}$$

Outputs express proportional change in 2006 relative to 1977, with positive and negative values indicating proportional increases and decreases in ESP, respectively. To visually represent the spatial distribution of ESP in each case study, maps were created in ArcMap 10 GIS software using the Spatial Analyst Tools (Map Algebra, Raster calculator). Habitats were assigned contribution scores of 1, 2 or 3 for each

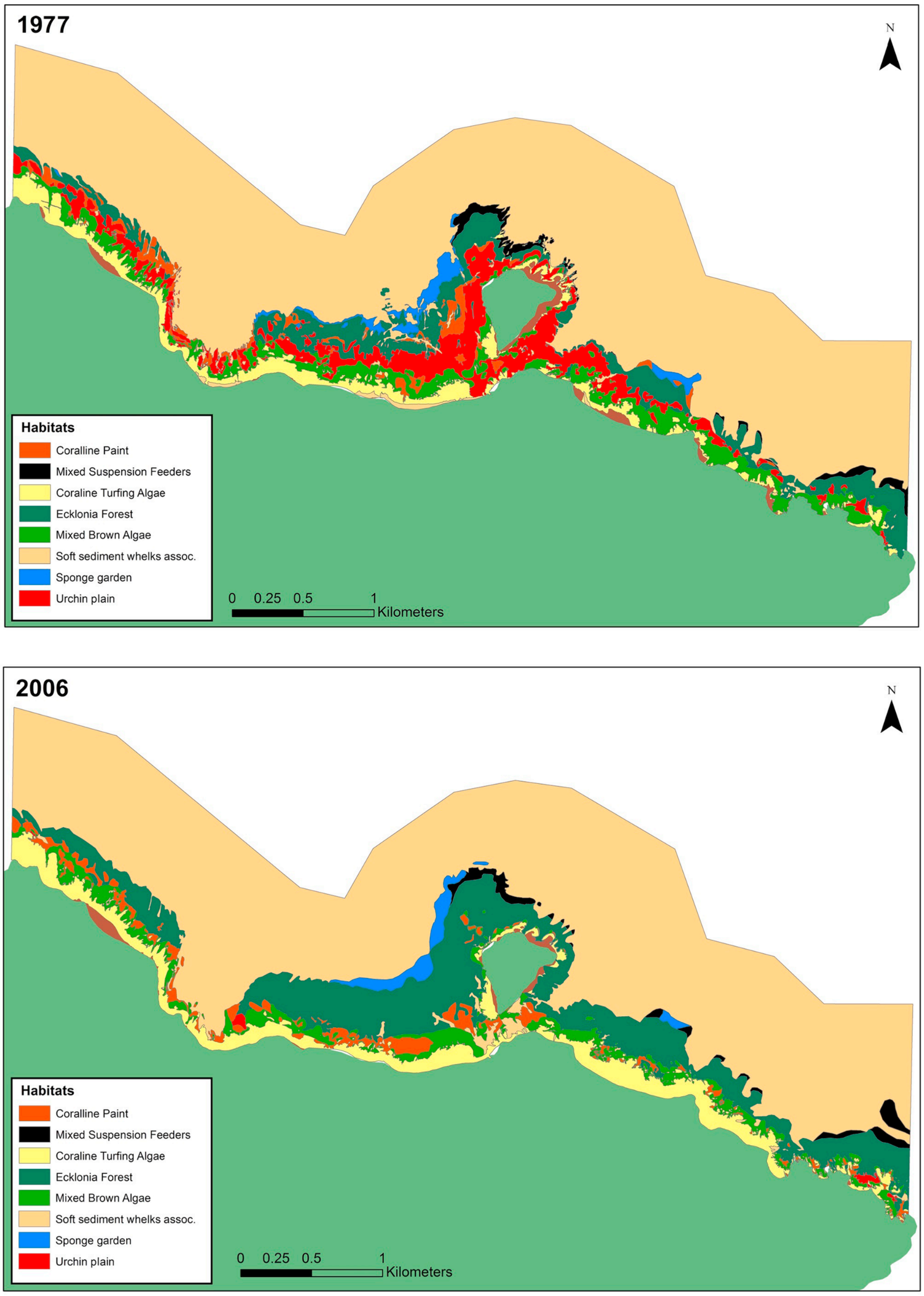

Fig. 2. Benthic habitats within the Cape Rodney-Okakari Point Marine Reserve in 1977 (top) and 2006 (bottom), as reported by Remy-Zephir et al. (2012). The marine reserve boundary is indicated by the outer black line.

service that made low, moderate or significant contributions to ESP, respectively.

3. Results

3.1. Ecosystem service matrix for New Zealand's coastal marine habitats

The matrix provides an overview of the ESP provided by different benthic marine habitats in New Zealand. Nine percent of cells within the matrix could not be assessed due to a lack of available literature or expert knowledge (Table 2). Of the remaining cells, understanding of ESP was derived predominately from expert opinion (60% of cells), with a limited amount of evidence from New Zealand published literature (20% of cells) and New Zealand grey or overseas published literature (20% of cells). Scientific understanding was better developed for certain services (habitats for species, medicinal resources, nutrient regeneration, waste water treatment, sediment formation & composition, carbon sequestration & storage services), and habitats (sponge

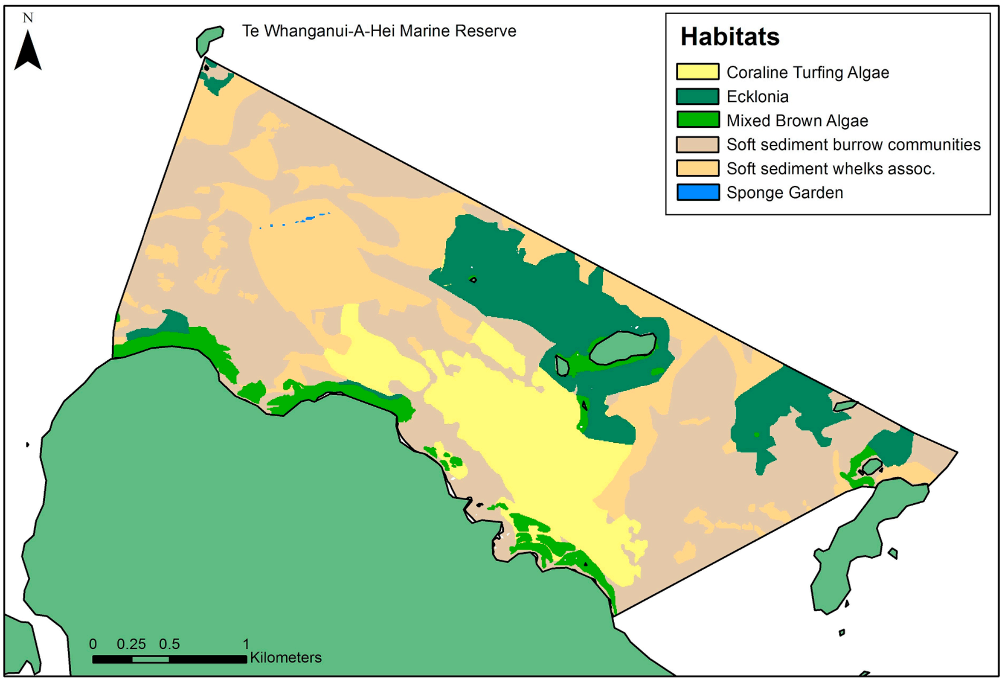

Fig. 3. Benthic habitats within the Whanganui A Hei Marine Reserve. The marine reserve boundary is indicated by the outer black line.

gardens, mangrove forest, bull kelp (*Durvillaea*) forest, *Macrocystis* forest, mixed brown algae, oyster reef and red algae meadows habitats). There was little evidence from the literature for the contribution of cerianthid beds, erect soft sediment invertebrates, mobile rocky reef invertebrates, sea pen beds, surf clam beds and tubeworm mats to ESP (Table 2).

Coastal benthic marine habitats collectively contributed to ESP for a wide range of services. While the majority of habitats made moderate or significant contributions to ESP for five or fewer services, cockle beds, mangrove forest, mussel beds, oyster reefs, saltmarsh and seagrass meadows contributed to seven or more of the 12 services assessed (Table 2). Conversely, brachiopod beds and coralline paint were assessed as only making low contributions to ESP (Table 2). Similarly, some services were supported by very few habitats (e.g., moderation of extreme events, medicinal resources), while other services are supported by many (e.g., habitats for species, carbon sequestration and storage). Thirty-two of the thirty-eight habitats were assessed as making moderate or significant contributions to the Habitat and supporting services category (Table 2). These contributions were primarily to the habitats for species (25 habitats) and nutrient regeneration services (15 habitats). Ten or fewer habitats made a moderate or significant contribution to the primary production and sediment formation & composition services (Table 2). For the Regulating services category, 28 habitats were assessed as making moderate or significant contributions (Table 2), with the majority of these being to the carbon sequestration service (20 habitats). Eleven or fewer habitats contributed to the erosion prevention, local climate and air quality and waste-water treatment services, with only two habitats (mangrove forest and saltmarsh) contributing to the moderation of extreme events service (Table 2). For the Provisioning services category, only 14 habitats made a moderate or significant contribution, with fewer than 8 habitats contributing to each of the food, raw materials and medicinal resources services (Table 2).

3.2. Case-study 1

In both 1977 and 2006, habitats within the Cape Rodney-Okakari Point Marine Reserve made moderate or significant contributions to nine of the twelve services assessed. Of the remaining services, low or negligible contributions were made to sediment formation and composition, erosion prevention, and the moderation of extreme events (Table 4). The spatial extent of habitats considered of significant importance to primary production, local climate and air quality, habitats for species, and carbon sequestration increased by approximately 30 ha between 1977 and 2006 (Table 4, Figs. 4 and 5). The extent of habitats considered of moderate importance to habitats for species and raw materials services also increased slightly (Table 4, Fig. 5). These changes were largely driven by increases in the spatial extent of coralline turfing algae and *Ecklonia* forest between 1977 and 2006 (Fig. 2). Conversely, the extent of habitats considered to be of significant or moderate importance to nutrient regeneration, food and medicinal resources decreased between 1977 and 2006 (Fig. 5), and were driven by reductions in the spatial extent of mixed brown algae, soft sediment whelk communities and urchin plain habitats (Fig. 2).

3.3. Case study 2

The Whanganui A Hei Marine Reserve is ~293 ha (1.5 times) larger in extent than the Cape Rodney-Okakari Point Marine Reserve (Fig. 1), with both reserves demonstrating spatial heterogeneity in service potential (Figs. 4 and 6). Habitats within both reserves made moderate or significant contributions to nine of the twelve services assessed (Table 5). Within the Whanganui A Hei Marine Reserve benthic habitats made only a low or negligible contribution to the sediment formation and composition, moderation of extreme events and the food services (although some habitats indirectly contributed to the food service by providing habitat for food species, as scored against the habitats for species service; Table 5). The spatial extent of habitats considered to be of significant or moderate importance to primary production, habitats for species, local climate and air quality services, and raw materials were approximately 2.5 times greater in the Whanganui A Hei Marine Reserve than the Cape Rodney-Okakari Point Marine Reserve (Fig. 7), while the extent of habitats considered to be of significant or moderate importance to medicinal resources, and waste-water treatment were

Table 3
Thresholds for low and high habitat quality for each of 7 habitat types. For each habitat, the mean combined biomass or density of the defining species from 3772 one square meter quadrats sampled by Shears and Babcock (2007) at 205 sites across New Zealand was calculated, and the corresponding lower and upper limits of 95% confidence intervals used to define low and high habitat quality thresholds, respectively. See Section 2 for further details.

Habitat	Defining species	Low habitat quality threshold	High habitat quality threshold
Coralline paint	Crustose coralline algae	$17.3\ \text{g m}^{-2}$	$17.8\ \text{g m}^{-2}$
Coralline turfing algae	Coralline turf	$22.7\ \text{g m}^{-2}$	$25.2\ \text{g m}^{-2}$
Ecklonia forest	*Ecklonia radiata*	$274.8\ \text{g m}^{-2}$	$323.9\ \text{g m}^{-2}$
Urchin plain	Evechinus chloroticus	$8.9\ \text{indiv. m}^{-2}$	$9.9\ \text{indiv. m}^{-2}$
Mixed brown algae	*Carpophyllum angustifolium* *C. flexuosum* *C. maschalocarpum* *C. plumosum* *Landsburgia quercifolia* *Lessonia variegate* *Sargassum sinclairii* *Xiphophora chondrophylla*	$264.9\ \text{g m}^{-2}$	$313.8\ \text{g m}^{-2}$
Soft sediment whelks assoc.	*Cominella adspersa* *C. maculosa* *C. quoyana* *C. virgata* *Maoricolpus roseus* *Penion sp.*	$4.9\ \text{indiv. m}^{-2}$	$6.3\ \text{indiv. m}^{-2}$
Sponge garden	*Aaptos aaptos* *Ancorina alata* *Cliona elata* Encrusting sp. Finger sp. Massive sp. *Tethya aurantium* *Tethya ingalli*	$64.2\ \text{g m}^{-2}$	$77.6\ \text{g m}^{-2}$

Note: There was no information from the Shears and Babcock (2007) dataset on the biomass or density of the defining species for the mixed suspension feeders or soft sediment burrow community habitats; therefore, we scored the entirety of these habitats as being of moderate quality.

approximately 5 and 52 times greater, respectively (Table 5, Fig. 7). These differences were primarily driven by a larger spatial extent of *Ecklonia*, mixed brown algae and soft sediment burrow communities in the Whanganui A Hei Marine Reserve than the Cape Rodney-Okakari Point Marine Reserve (Figs. 2 and 3). Conversely, the extent of habitats considered to be of significant or moderate importance to carbon sequestration and storage and food was greater in the Cape Rodney-Okakari Point Marine Reserve than the Whanganui A Hei Marine Reserve, and was driven by larger areas of soft sediment whelk communities and urchin plain habitats (Figs. 2 and 3).

A greater proportion of habitats making a significant contribution to ESP were of high quality within the Whanganui A Hei Marine Reserve (0.19) than the Cape Rodney-Okakari Point Marine Reserve (0.08) where a greater proportion were of low quality (0.42, compared to 0.22 within the Whanganui A Hei Marine Reserve). Similarly, a larger proportion of habitats making a moderate contribution to ESP were of high quality in the Whanganui A Hei Marine Reserve (0.11) relative to the Cape Rodney-Okakari Point Marine Reserve (0.07), although within Whanganui A Hei Marine Reserve a larger proportion of habitats making a moderate contribution to ESP were of low quality (0.28) than in the Cape Rodney-Okakari Point Marine Reserve (0.14).

4. Discussion

Although habitat-service matrices have been widely used in terrestrial systems, few applications in marine systems have moved beyond using them to provide a qualitative description of ESP based upon the presence or absence of habitats (Potts et al., 2014; but see Cabral et al., 2014; Galparsoro et al., 2012). Such approaches limit the ability to distinguish between areas with high or low service potential, and can lead to situations in which two distinct areas appear superficially similar in terms of the services they provide. We have begun to address this limitation by combining our matrix with information on the spatial extent and quality of habitats to provide a better indication of ESP. As illustrated by the case studies, this minor adjustment to matrix methodology better differentiates areas in terms of the extent and quality of ESP.

Outputs from the ESP matrix approach can be used to track the benefits being derived from existing MPAs, or incorporate ESP into protected area planning. For example, we were able to apply the ESP matrix approach to the Cape Rodney-Okakari Point Marine Reserve and identify the increased potential for primary production, habitats for species, carbon sequestration and local climate and air quality services resulting from the re-establishment of community-level trophic cascades that were recorded by Babcock et al. (1999) and Shears & Babcock (2002). These authors documented that the removal of fishing pressure from the establishment of the reserve increased predator density (spiny lobsters *Jasus edwardsii* and snapper *Pagrus auratus*), resulting in increased predation of sea urchins (*Evechinus chloroticus*) and the recovery of macroalgal habitats. Where there is certainty in how the structure and/or functioning of ecosystems will respond to protection (which is often complex and can continue to develop for decades), the ESP matrix could be used to predict changes in ESP following a

Table 4
Outputs of Ecosystem Service Potential (ESP) for the Cape Rodney-Okakari Point Marine Reserve in 1977 and 2006. Moderate and significant contributions to ESP are shown.

Services	1977 contribution (ha)			2006 contribution (ha)			Proportional change		
	Moderate	Significant	SUM	Moderate	Significant	SUM	Moderate	Significant	SUM
Primary production	0.00	75.56	75.56	0.00	116.85	116.85	0	0.55	0.55
Nutrient regeneration	387.69	0.00	387.69	370.84	0.00	370.84	−0.04	0	−0.04
Habitats for species	34.80	81.59	116.39	48.25	123.70	171.95	0.39	0.52	0.48
Sediment formation and composition	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0
Carbon sequestration & storage	0.00	424.15	424.15	0.00	453.91	453.91	0	0.07	0.07
Erosion prevention	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0
Local climate and air quality	31.96	43.60	75.56	27.18	89.67	116.85	−0.15	1.06	0.55
Waste-water treatment	0.00	6.03	6.03	0.00	6.85	6.85	0	0.14	0.14
Moderation of extreme events	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0
Food	43.66	0.00	43.66	1.15	0.00	1.15	−0.97	0	−0.97
Raw materials	75.56	0.00	75.56	116.85	0.00	116.85	0.55	0	0.55
Medicinal resources	38.00	0.00	38.00	34.04	0.00	34.04	−0.10	0	−0.10

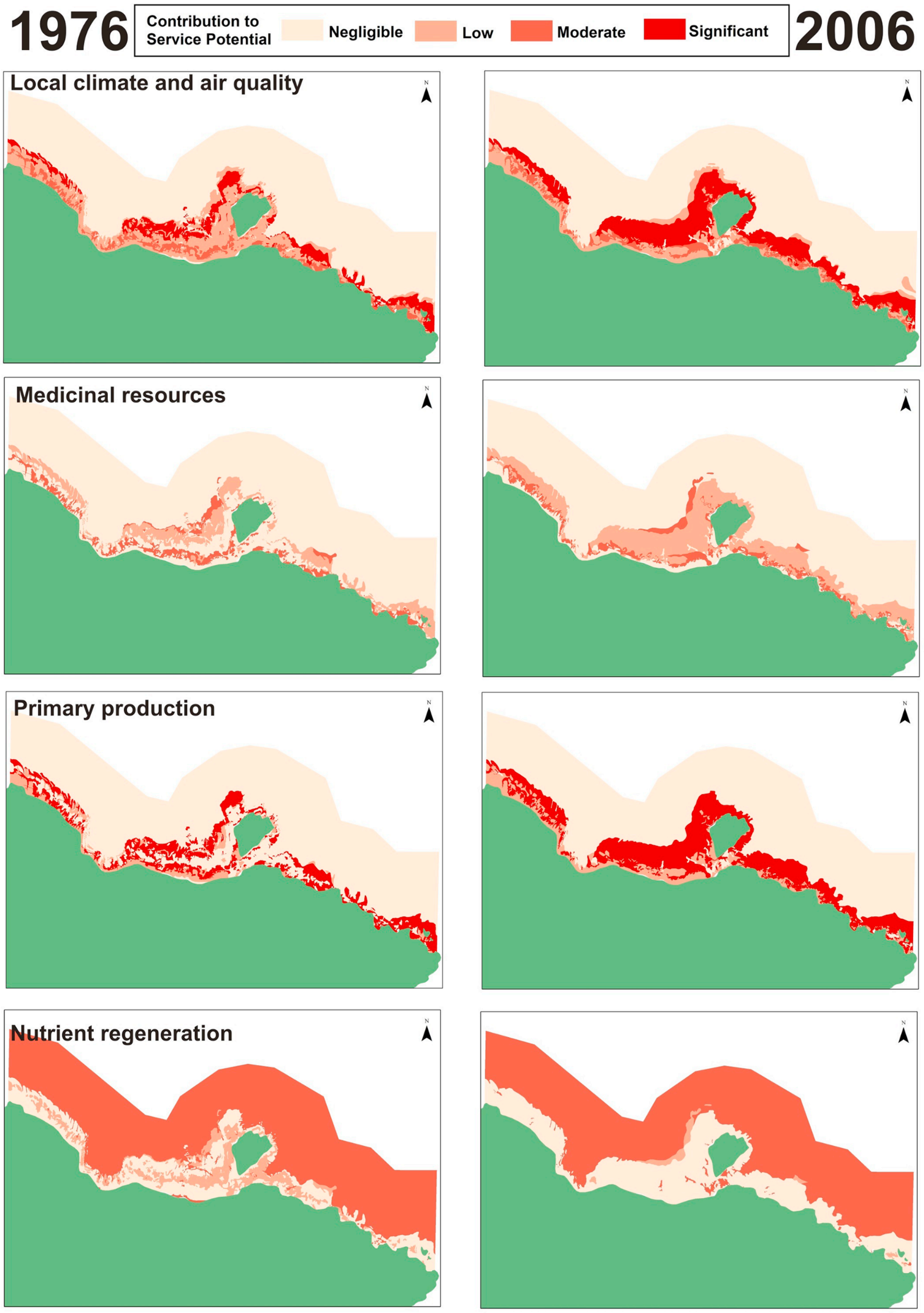

Fig. 4. Maps of Ecosystem Service Potential (ESP) for the Cape Rodney-Okakari Point Marine Reserve in 1977 (left) and 2006 (right), produced using the ecosystem matrix approach. Maps illustrate ESP for local climate and air quality, medicinal resources, primary production and nutrient regeneration. Scoring indicates relative spatial contribution to ESP, from high (darkest shading) to low (lightest shading).

sufficient recovery lag, or conversely, identify the maintenance of ESP following substitutions of functionally similar species.

When matrix outputs include both ‘intermediate’ and ‘final’ services (e.g., Tables 4 and 5), care may be needed to avoid ‘double counting’. For example, *Ecklonia* forest habitat within the Cape Rodney-Okakari Point Marine Reserve supported the primary production service as well as the habitats for species, carbon sequestration and storage, and local climate and air quality services. Double counting can cause uncertainty and poor reliability in estimating ESP value. Therefore, when applying valuation methods researchers should recognise the interactions between intermediate and final services and reduce double counting by, for example, selecting and valuing only the final benefits obtained (Boyd and Banzhaf, 2007), or delineating intermediate and final services (Wallace, 2007).

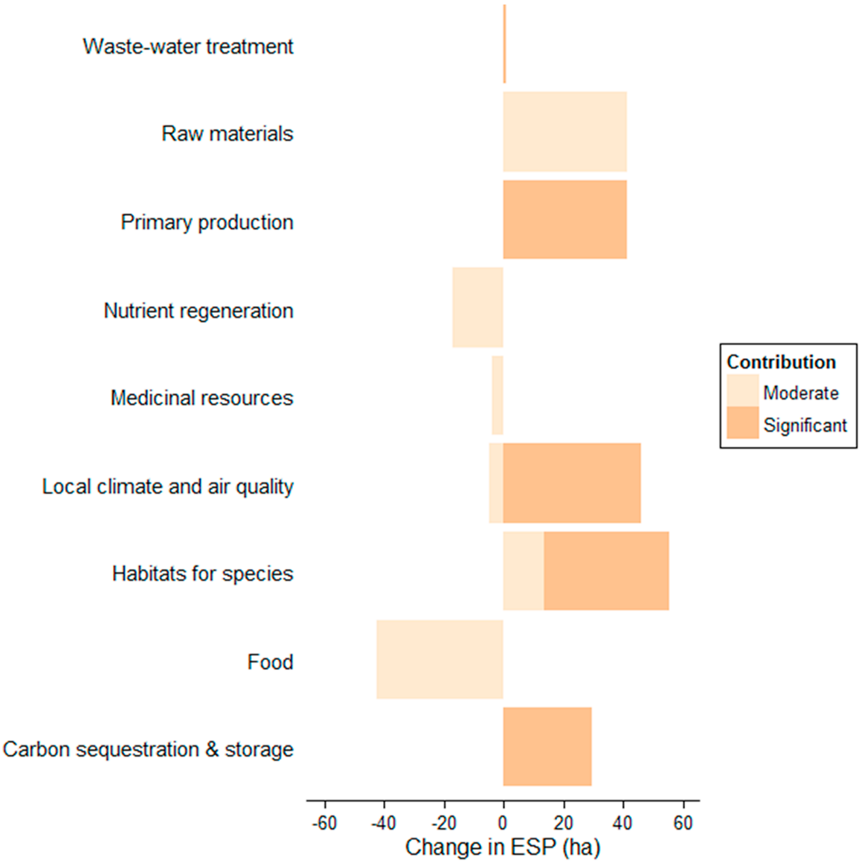

Fig. 5. Change in the spatial extent of Ecosystem Service Potential (ESP) at Cape Rodney-Okakari Point Marine Reserve between 1977 and 2006 for 9 services, disaggregated by habitats considered to make a significant or moderate contribution to ESP. Positive and negative values indicate proportional increases and decreases in ESP, respectively. *NOTE*: habitats within the reserve did not contribute to *sediment formation and composition*, *erosion prevention*, and *moderation of extreme events* services – these are therefore omitted from the figure.

Incorporating habitat area into ESP assessments is a necessary step but is complicated when ecosystem functions are non-linear over space and time (Farnsworth, 1998). For example, Barbier et al. (2008) and Koch et al. (2009) demonstrate non-linear behaviour in wave attenuation moving into mangrove and saltmarsh habitat patches, and the effect of this on land use and valuation in coastal ecosystems. Ultimately services, such as the moderation of extreme events, may be more strongly dependent on the size and shape of individual habitat patches than just the total area across a region. Edge-effects and thresholds are a well-known phenomenon in ecology (Ries et al., 2004; Casini et al., 2009) and service provision may respond either positively or negatively, depending on the service, moving from a high number of smaller habitat patches to a lower number of larger ones. Exploring and incorporating all forms of spatial nuances in service delivery is beyond the scope of our broad matrix approach. However, further consideration could be given to the inclusion of minimum requirements for habitat patch width and thickness for the moderation of extreme events service. Additional improvements in the approach can be made as our understanding of relationships between area and services improve over time.

Despite the importance of ecosystem services to human well-being, incorporating their values into protected area planning and implementation remains a considerable challenge. There has been little progress in global-scale mapping of ESP (although see Spalding et al., 2016), and even at local scales, the mapping and quantification of ESP remains challenging (Hauck et al., 2013; Schulp et al., 2014; Townsend et al., 2014). Consequently, there has been little systematic targeting of ecosystem services during MPA designation processes to date, as called for in the Convention of Biological Diversities Aichi Target 11 (http://www.cbd.int). Although the development of the ESP matrix that we have undertaken allows the evaluation of ESP within marine reserves, improvements in the assessment of habitat quality and the impact of specific human activities could help facilitate wider application in future protected area network planning, marine spatial planning processes, integrated coastal zone management and threat adaptation initiatives. For example, where there is an aim to maximize the potential for specific services or a range of services, the matrix could be used to inform the development and management of service-orientated MPAs or MPA networks. This would function by using the matrix to evaluate the spatial contribution of candidate sites to service potential and ensuring priority services are supported by a range of habitats that maximize resilience of ESP to environmental uncertainty. The matrix could also be applied to each site within an MPA network to evaluate how well the network protects a representative range of services and the amount of replication for each service across the network. Further, by ranking the susceptibility of habitats within a location to stressors and accounting for the potential for multiple stressors and cumulative impacts, the services most at risk can be identified. Habitats will always be affected by some stressors more than others (for example, seagrass may be strongly impacted by turbidity and sedimentation but not elevated heavy metal contaminants), and this may have concomitant impacts on ESP. Additionally, the value of the matrix could be improved by filling information gaps and expansion to include a broader range of species and habitats.

MPAs are thought to help maintain or restore ecosystem services by reducing pressures on ecosystem functioning (Leenhardt et al., 2015). MPAs such as the Great Barrier Reef, which at 34.44 million ha includes the world's largest coral reef system, or the Pitcairn Islands which covers 83 million ha (Fernandes et al., 2005, Pala, 2013) are likely to make meaningful contributions to large scale processes and ES delivery. Alternatively, small MPAs, such as New Zealand's 39 mainland marine reserves, which average ~1576 ha in extent, are likely to individually

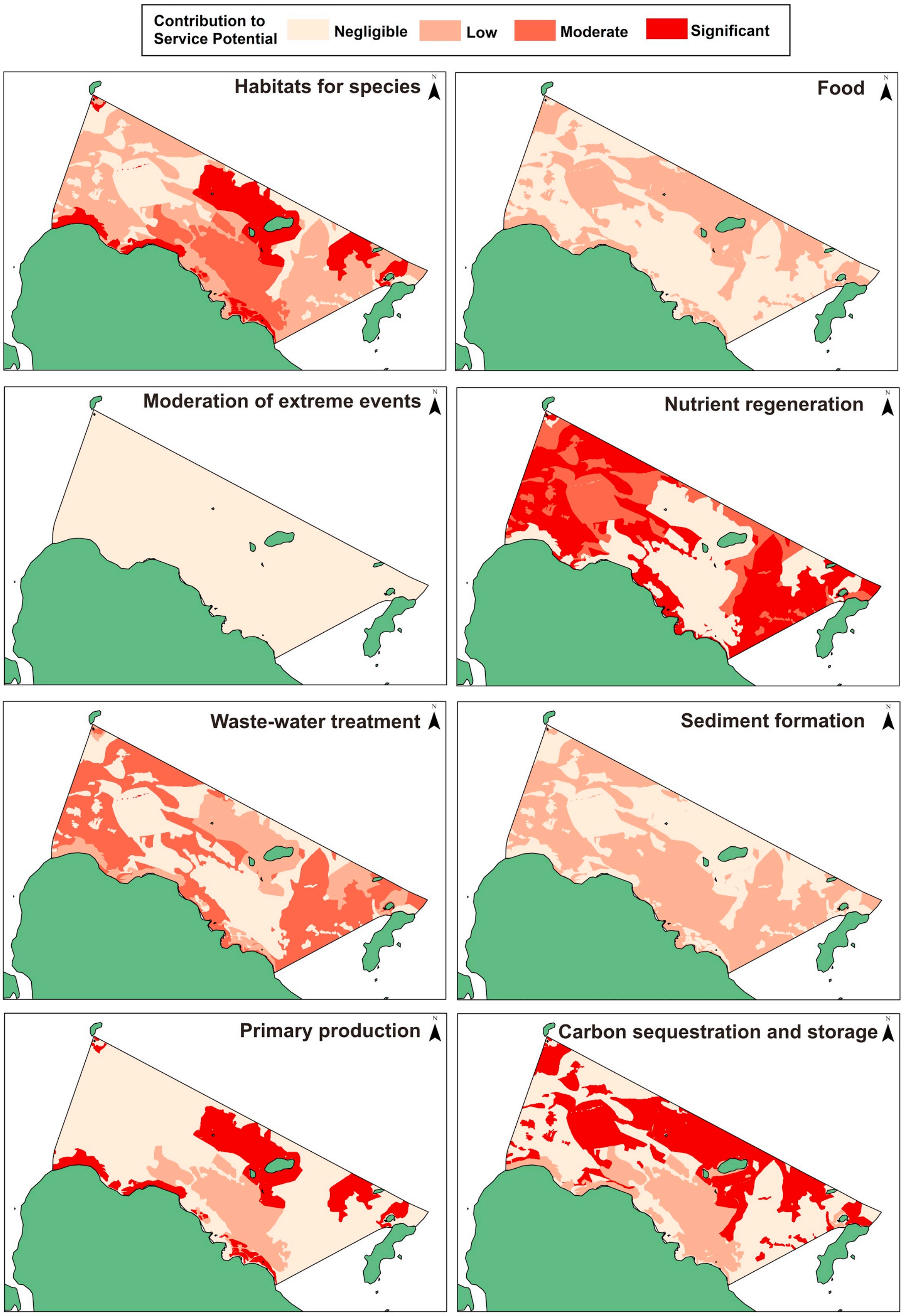

Fig. 6. Maps of Ecosystem Service Potential (ESP) for the Whanganui A Hei Marine Reserve, produced using the ecosystem matrix approach. Maps illustrate ESP for habitats for species, food, moderation of extreme events, nutrient regeneration, waste-water treatment, sediment formation, primary production and carbon sequestration and storage. Scoring indicates relative spatial contribution to ESP, from high (darkest shading) to low (lightest shading).

Table 5
Ecosystem Service Potential outputs for benthic habitats within the Cape Rodney-Okakari Point Marine Reserve and the Whanganui A Hei Marine Reserve. Habitats are divided into high, medium, and low habitat quality. Services are shown for significant and moderate contributions.

Services	Moderate Contribution (ha) Habitat Quality				Significant Contribution (ha) Habitat Quality				SUM (ha)
	Low	Mid	High	SUM	Low	Mid	High	SUM	
Cape Rodney-Okakari Point Marine Reserve									
Primary production	0.00	0.00	0.00	0.00	95.72	6.19	14.94	116.85	116.85
Nutrient regeneration	0.00	370.84	0.00	370.84	0.00	0.00	0.00	0.00	370.84
Habitats for species	20.82	6.61	20.82	48.25	96.06	10.54	17.11	123.70	171.95
Sediment formation and composition	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Carbon sequestration & storage	0.00	0.00	0.00	0.00	71.42	369.79	12.70	453.91	453.91
Erosion prevention	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Local climate and air quality	24.30	0.64	2.24	27.18	71.42	5.55	12.70	89.67	116.85
Waste-water treatment	0.00	0.00	0.00	0.00	0.33	4.35	2.17	6.85	6.85
Moderation of extreme events	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Food	0.00	1.15	0.00	1.15	0.00	0.00	0.00	0.00	1.15
Raw materials	95.72	6.19	14.94	116.85	0.00	0.00	0.00	0.00	116.85
Medicinal resources	24.64	4.99	4.41	34.04	0.00	0.00	0.00	0.00	34.04
Whanganui A Hei Marine Reserve									
Primary production	0.00	0.00	0.00	0.00	97.37	134.22	71.71	303.30	303.30
Nutrient regeneration	0.00	183.29	0.00	183.29	0.00	358.43	0.00	358.43	541.72
Habitats for species	50.86	0.00	73.47	124.33	97.44	134.38	71.72	303.55	427.88
Sediment formation and composition	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Carbon sequestration & storage	0.00	0.00	0.00	0.00	55.27	191.19	56.85	303.30	303.30
Erosion prevention	0.00	358.43	14.86	373.29	0.00	0.00	0.00	0.00	373.29
Local climate and air quality	42.11	126.32	14.86	183.29	55.27	7.90	56.85	120.01	303.30
Waste-water treatment	0.00	358.43	0.00	358.43	0.07	0.17	0.02	0.25	358.68
Moderation of extreme events	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Food	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Raw materials	97.37	134.22	71.71	303.30	0.00	0.00	0.00	0.00	303.30
Medicinal resources	42.17	126.49	14.88	183.54	0.00	0.00	0.00	0.00	183.54

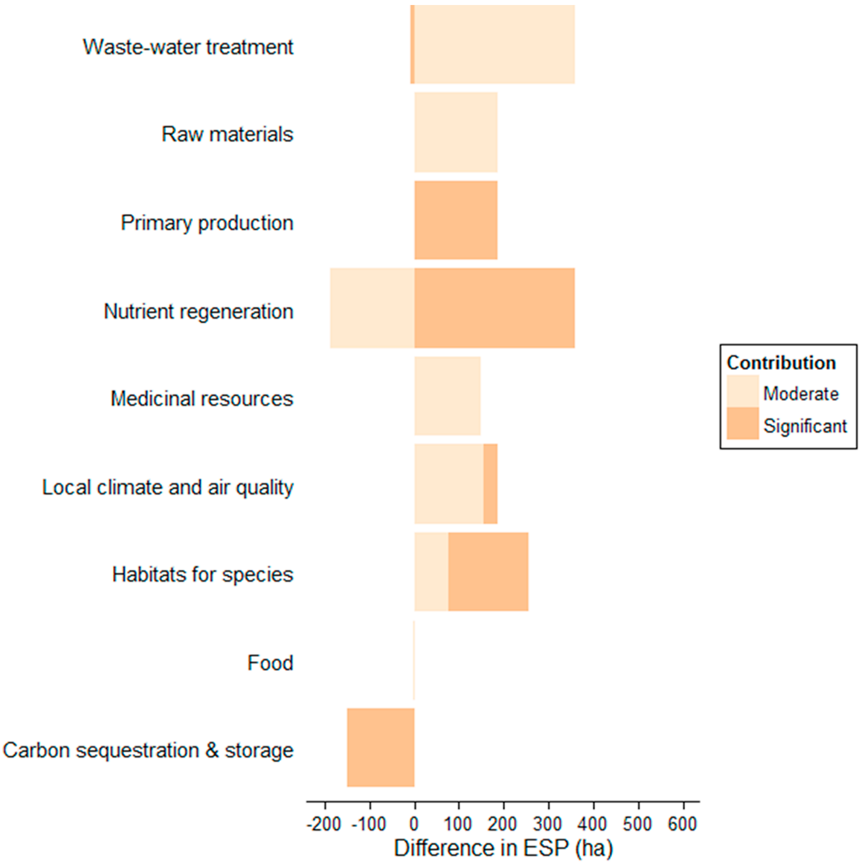

Fig. 7. Difference in the spatial extent of Ecosystem Service Potential (ESP) at Cape Rodney-Okakari Point Marine Reserve and the Whanganui A Hei Marine Reserve for 9 services, disaggregated by habitats considered to make a significant or moderate contribution to ESP. Positive and negative values indicate differences in ESP within Whanganui A Hei Marine Reserve relative to Cape Rodney-Okakari Point Marine Reserve. *Note*: habitats within either reserve did not contribute to *sediment formation and composition*, *erosion prevention,* and *moderation of extreme events* services – these are therefore omitted from the figure.

offer nominal contributions to ESP at regional to global scales. However, at the network scale, it is expected that small MPAs will contribute to substantial system-wide ESP if the representation of habitats across MPAs capture the diversity and heterogeneity of habitats that support ESP, and habitats are replicated among MPAs to safeguard services against natural or anthropogenic perturbations. Within this context, individual MPAs should also be evaluated for their contribution towards maximizing services already protected, or expanding the range of services provided across wider MPA networks. This could be the focus of future applications of the ESP matrix.

There is an obvious alignment between the concepts of ES and biodiversity conservation, with both seeking to raise awareness of the importance of nature and balance human needs with the persistence of natural systems. However, it is important to recognise that ES and biodiversity conservation are not identical concepts and may not always be compatible (Naidoo et al., 2008; Dickie et al., 2011, Tallis and Lubchenco, 2014). There are habitats within the matrix that do not make significant contributions to the ecosystem services included, but this is not to say that they do not have an important role within the natural system in terms of functioning or resilience, or other types of ecosystem services not considered. If ES approaches are applied to achieve biodiversity outcomes they may under-represent species or ecological processes without utilitarian or economic value, or that do not directly benefit people.

The assessment of status and trends of cultural ecosystem services has been one of the most difficult and least accomplished tasks in ecosystem services research (Schaich et al., 2010), and we intentionally omitted cultural services from our ESP matrix. Although specific services can have straight-forward relationships with habitats (e.g., leisure and recreation), the relationship of other services have far greater complexity and are challenging to score without context-specific information. For example, cultural services are the outcome of a series of complex and dynamic relationships between ecosystems and humans in landscapes through time, making them difficult to define (Plieninger et al., 2013). Culture can be determined by our family, upbringing and life experiences, and can differ between generations, ethnicities, religions, countries of origin, income level, location of residence and sector of society (Hofstede, 1991, Hebel, 1999). Consequently, there is a potential mismatch between cultural values at a particular location and those at the national level at which we constructed our ESP matrix. We therefore suggest that cultural services are best integrated with our matrix by using local stakeholders to evaluate the contribution of habitats to locally relevant cultural services. Cultural services can then be incorporated with the ESP matrix as separate components within a broader evaluation of ESP.

Preserving the intrinsic value of biodiversity has not been incentive enough to meet many of the world's global conservation targets, suggesting that new approaches, which communicate the diverse values of conservation, and how our actions impact these values, are required. The ES concept provides opportunity to communicate the non-market value of supporting and regulating services, making biodiversity relevant to decision-making that might have previously only considered it in terms of regulatory compliance, impact mitigation and/or reputational liability (e.g., Houdet et al., 2012). Our advancement of the ES matrix approach is an important step in communicating the non-market value of supporting and regulating services, and can be used to demonstrate tangible benefits derived from existing biodiversity protection, and could help inform the design of ecologically coherent MPA networks capable of safeguarding ESP.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2018.12.004.

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