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Research Article

Valuation of kelp forest ecosystem services in the Falkland Islands: A case study integrating blue carbon sequestration potential

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Abstract

Kelp forests provide many important ecosystem services to people, including mitigating storm damage, cycling nutrients, and providing commercially-harvestable resources. However, kelp forests' ability to sequester carbon dioxide, and therefore help regulate the climate, has until recently, been overlooked in assessments of the beneficial services they provide. In this study we incorporate updated knowledge on the potential of kelp to sequester 'blue carbon', and use the extensive kelp forests of the Falkland Islands as a case study to assess the value of kelp forest to society through multiple associated ecosystem services. Our analysis shows kelp forests provide a highly valuable range of direct and indirect services, which if managed correctly, will continue to benefit people, both now and in the future. The total estimated value of the Falkland Islands' kelp system is currently equivalent to ~ £2.69 billion per year (or £3.24 million km^{-2} year^{-1}). However, the true value of the kelp forest surrounding the Falkland Islands is likely to be higher still, given that our estimate does not account for elements such as associated scientific research, tourism, and cultural services, due to the necessary data currently being unavailable. Similarly, the full value of these highly biodiverse ecosystems in supplying habitat and food to a large range of associated species is crucial, yet extremely difficult to fully quantify. This study illustrates the importance of maintaining kelp ecosystems in a

healthy state to ensure they continue to supply valuable ecological processes, functional roles, and ecosystem services, including their overlooked role as significant long-term carbon sinks.

Keywords

ecosystem services, kelp, macroalgae, natural capital, carbon sequestration, Falkland Islands

Introduction

Ecosystem services are "the benefits people obtain from ecosystems” and which improve people's overall well-being (MEA 2005). Coastal and marine ecosystems provide a range of services, including: ‘regulating services’, such as storm protection and climate regulation; ‘provisioning services’, such as commercial food and energy supply; and ‘cultural services’, such as recreation and spiritual significance (Beaumont et al. 2007, Martínez et al. 2007, Barbier et al. 2011, Haines-Young and Potschin 2013, Himes-Cornell et al. 2018). Ecosystems including reefs, wetlands, seagrass, and macroalgae beds (e.g. kelp forest), only cover a small portion of the world’s surface area, but are estimated to provide nearly half of the world’s total ecosystem services (Costanza 1999). The MAES (Mapping and Assessing Ecosystem Services) approach used to assess such ecosystem services, is useful for improved decision-making and to inform policy related to sustainable management of these services, by accounting for and valuing both ecological processes and human activities (Maes et al. 2012). The outputs of the approach help to meet policy commitments, such as the EU Biodiversity Strategy for 2030 (European Commission 2020), by accounting for these services within a methodological framework.

Kelp forests are mixed assemblages of brown algae from the Order Laminariales, found globally within rocky coastal marine systems in temperate, sub-tropical and sub-polar regions (Graham et al. 2007). Within the waters around Patagonian South America and the Falkland Islands, *Macrocystis pyrifera* or ‘giant kelp’ is typically the largest and most abundant component of the kelp forest assemblage. This is followed by the smaller *Lessonia* spp. kelps which form an understorey layer (Graham et al. 2007, Vásquez et al. 2014). Kelp forests are a foundation habitat which performs a range of important ecological functions (Beaton et al. 2020, Graham et al. 2007) and are known to provide many direct and indirect ecosystem services (Filbee-Dexter 2020, Smale et al. 2013, Vásquez et al. 2014).

Globally, coastal and marine vegetation captures and sequesters significant amounts of atmospheric carbon dioxide through natural processes, helping to regulate climate. Kelp forests were previously thought to contribute little to carbon sequestration as this habitat is typically located on rocky substrate, as opposed to the soft sediment surrounding habitats such as seagrass and mangrove forest that is necessary for long-term carbon storage (Macreadie et al. 2017b). The scope for long-term kelp vegetation settlement, and hence carbon storage, within this rocky substrate, was therefore considered minimal (Krause-Jensen and Duarte 2016). However, recent analyses demonstrate considerable potential for macroalgae such as kelp to be sequestered to deeper waters, i.e. beyond the turbulent ocean surface mixing layer, and for this habitat type to have a much more substantial role as a carbon sink through this route than previously thought (Filbee-Dexter and Wernberg 2020, Krause-Jensen and Duarte 2016, Queirós et al. 2019). Current global sequestration estimates for all marine macroalgae are ~173 Tg C yr^{-1} (ranging from 61–268 Tg C yr^{-1}), with the majority of this sequestration being facilitated through transport into the deep sea (Krause-Jensen and Duarte 2016, Queirós et al. 2019).

Kelp additionally provides a range of other important services. These can originate either directly from the kelp itself or indirectly from the diverse range of species which use the kelp forest for food and habitat, or those which are bio-physically influenced by its presence (Gaylord et al. 2007, Graham et al. 2007, Nikula et al. 2010). These services may include functional processes such as nutrient cycling and coastal protection. Alternatively they may include the value attained through activities like commercial fishing, recreational fishing, and the eco-tourism benefit from associated species, such as sea lions and sea otters (Blamey and Bolton 2018, Filbee-Dexter 2020, Smale et al. 2013, Vásquez et al. 2014, Macreadie et al. 2017a).

This work aims to quantify and estimate the total value of the ecosystem services associated with the Falkland Islands' kelp forests, including their value in sequestering carbon dioxide, known as 'blue carbon'. We use a combination of high-resolution satellite-derived kelp habitat extent predictions along with a large dataset of in-situ density measurements to examine the ecosystem service value of these kelp forests. This work builds on previous analyses in this region, showing extensive kelp assemblages (Golding et al. 2019) and significant economic benefits from the Falkland Islands' natural systems (Bayley et al. 2017, Bormpoudakis et al. 2019, Smith 2019). We focus our analysis on quantifying the direct services of kelp-associated harvested goods, as well as the indirect services of nutrient cycling and climate buffering. Our results are presented to aid management of these important ecosystems and to improve the understanding of their value and benefit to society.

Material and methods

We used a range of economic valuation techniques to assess the combined ecosystem service value of a mixed *Macrocystis pyrifera* and *Lessonia* spp. kelp forest. We include: (1) the regulating service value of kelp as a climate buffer (through carbon storage and sequestration); 2) the regulating service value of nutrient cycling; 3) the provisioning service of associated commercial fisheries; and 4) the theoretical provisioning service of kelp as a raw material via extraction of alginate/alginic acid. A summary of datasets used for each valuation method (and their limitations) is available in Suppl. material 1A.

Study location

The Falkland Islands, situated in the temperate and sub-polar South Atlantic, comprises two main islands (East and West Falkland) and 776 smaller surrounding islands (Fig. 1). This archipelago is relatively sparsely populated (2020 population = 3,480 or ~ 0.28 individuals km^{-2}) and is isolated geographically. The region is consequently relatively un-impacted by global human pressures (Jones et al. 2018).

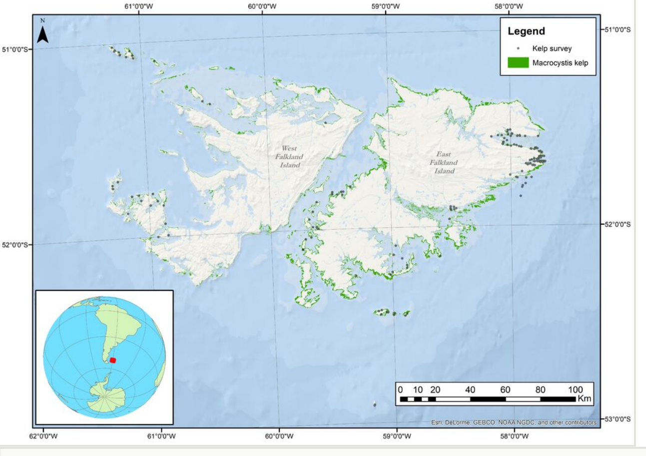

Figure 1.

Mapped distribution of kelp forest (*Macrocystis pyrifera*) across the Falkland Islands, based on habitat modelling undertaken in 2019 (Golding et al. 2019). Site location points of annual benthic surveys of kelp, conducted between 2008 and 2016 are shown (projection: WGS84 UTM zone 21S).

The Falkland Islands is one of the UK's 14 overseas territories (UKOTs). As such, if they choose to have the UK's ratification of the Paris Agreement extended to them along with other UKOTs, they will be included in the UK's future accounting and reporting on emissions under the UN Framework Convention on Climate Change (UNFCC 2015).

The surrounding marine area covers 463,897 km^2 within the Exclusive Economic Zone, and includes both shallow and deep sea regions. The waters and coasts are home to a diverse mix of species (Otley et al. 2008) and extensive globally-significant *Macrocystis pyrifera* kelp forest habitat (Beaton et al. 2020). There is also a managed multi-species squid and finfish fishery which has been in place since 1987 and contributes to ~ 40% of Gross Domestic Product.

Kelp distribution

Current kelp distribution was mapped using image classifications based on Sentinel 1 (band 1) and Sentinel 2 (all 10 m bands) satellite imagery; Shuttle Radar Topography Mission (SRTM) data; and Landsat 8, (band 1) inputs within Google Earth Engine (Golding et al. 2019).

All satellite imagery was clipped to the Falkland Island area of interest and a cosine terrain correction was applied to the Sentinel 2 imagery to balance the effects of shadowing and bright surfaces. Cloud masking was also applied. Normalised Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Normalised Difference Water Index (NDWI), and Geary's C on Landsat 8's band 1 (coastal aerosol) were calculated as further metrics for input into the model classifier. Ground-truthing points from in-water survey were additionally included for training and validation of habitat classifiers for Random Forest analysis. For further details on the broad-scale mapping methodology, see Golding et al. (2019).

Accurate satellite data for the distribution of *Lessonia* spp. species was not possible with this method, due to the high amount of data processing artefacts created and concealment within the larger giant kelp-dominated forest. We therefore assumed the same extent for all kelp species. *Lessonia* spp. can, however, be found outside the range of *M. pyrifera*, and *M. pyrifera* can live at depths of ~ 50 m+ and be non-surface touching (Graham et al. 2007). Both species' full vertical (depth) and lateral distribution is therefore likely to be underestimated.

Carbon storage / sequestration

Kelp density

Kelp density was calculated based on field survey data collected from across the Falkland Islands between 2008 and 2016 (Shallow Marine Surveys Group, unpublished data), with a total of 315 surveys conducted between 2008 and 2016 (Fig. 1). Density values for *Macrocystis pyrifera* and *Lessonia* spp. were based on the number of individual giant kelp thali observed in-situ one metre either side along a 20 m transect (i.e 40 m^2 total sample area), placed randomly on the seabed within the kelp forest rocky habitat. Density (thali/m^2) for each species was averaged for autumn (March – May) and spring (September – November) surveys to account for any seasonal changes in density as the forest grows and senesces. Kelp health values are assumed to be homogenous throughout the extent of mapped kelp. Due to the remoteness of these islands (Jones et al. 2018), any such differences would be solely biophysically driven (i.e. through wave exposure).

Biomass and carbon content estimation

Macrocystis pyrifera thalli mean wet weight (excluding bare stipes) was calculated using values from van Tussenbroek (1993) for spring and autumn and multiplied by the mean kelp density observed from surveys conducted during the same season (Table 1). We use the estimated current biomass of kelp to equate stored carbon in standing kelp stock, rather than daily rates of productivity per species (C m^{-2} day^{-1}) as used in other studies (Vásquez et al. 2014). This is because turnover of standing biomass is rapid and the total storage value using daily productivity modelled over a multi-year period would likely be an overestimate of total carbon. The mean weight of carbon per metre squared was multiplied by the calculated extent of *Macrocystis pyrifera* within the Falkland Islands to give a total carbon standing stock, then converted to CO_2 using a conversion factor of 3.67 (based on relative atomic weights).

Kelp sequestration rate

The average net primary productivity (NPP) of *Macrocystis pyrifera* kelp forest (including understorey species), is estimated to be in the range 670 – 1300 g C m^{-2} yr^{-1}, with a mean productivity value of 985 g C m^{-2} yr^{-1} (Reed and Bzezinski 2009). Following a global analysis by Krause-Jensen and Duarte (2016), sequestration through burial of Particulate Organic Carbon (POC) in deep waters is estimated as ~ 0.92% of annual NPP; sequestration through export of POC to the deep sea is ~ 2.30% of NPP; and sequestration through export of Dissolved Organic Carbon (DOC) is ~ 7.69% of NPP (Fig. 2). Sequestration pathway proportions were then multiplied across the current known extent of kelp forest within the Falkland Islands and converted to CO_2 equivalent (CO_2e) weight. For macro-algae growing within shallow soft sediments, approximately 0.4% of annual NPP is also buried, with the carbon sequestered to this substrate (Krause-Jensen and Duarte 2016). However, in the context of the Falkland Islands, where kelp primarily grows on hard bedrock, this shelf-burial process is less likely and is excluded from calculations.

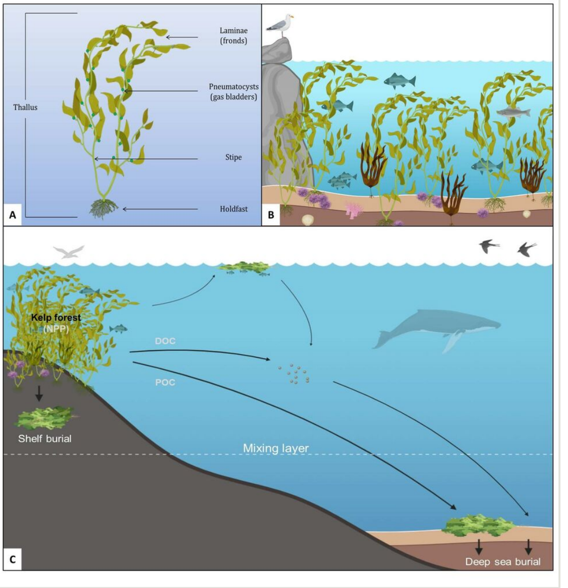

Figure 2.

Diagrams of: A) a typical giant kelp (*Macrocystis pyrifera*) thallus, illustrating the major components of the adult sporophyte plant life-stage; B) a typical giant kelp forest community structure, including kelp understorey and associated biodiversity; and C) sequestration routes of kelp forest net primary productivity (NPP) biomass to the deep sea through dissolved and particulate organic carbon (DOC/POC) pathways – based on Krause-Jensen and Duarte (2016).

Carbon value

The United Kingdom has now shifted from the direct use of the Social Cost of Carbon (SCC), which estimates lifetime damage costs of carbon to society, to a 'target-consistent' approach, based on emissions targets for future climate scenarios and the cost of abatement (BEIS 2019). Following this change, we use the current proposed high-series non-traded price of carbon for this study, set at £103.918 tonne^{-1} CO_2e. We use the high series non-traded (i.e. all emissions outside the remit of the EU ETS sectors of power stations/industrial plants and EU airlines) values of carbon as the values were initially proposed in 2009 (DECC 2009). Since this period, international emissions targets have become more ambitious, aiming to limit global temperature change to below 2^{o}C above pre-industrial levels (UNFCC 2015). Additionally, projected vs. real fuel pricing has changed, there has been insufficient action to meet previous abatement targets, and alternative energy technologies have reduced in cost. This means the central carbon cost series are likely under-costing the current central values (DECC 2009, BEIS 2019).

CO_2e cost values were applied to current estimates of carbon content and sequestration potential within the Falkland Islands (based on current density and distribution and assuming no future decline in kelp extent or density). It is important to note that the current value of the carbon *already* sequestered to the deep sea was not estimated due to lack of data, but is likely substantial.

Nutrient cycling

Our valuation is based on the replacement cost needed to recreate the function of coastal nitrogen and phosphorus regulation and recycling back to the land, if this natural service did not exist (Costanza et al. 1998). We use the cost value of $28,916 USD ha^{-1} year^{-1} stated by Costanza et al. (2014). The total extent over which this service value applies to for the Falkland Islands was again based on satellite estimates of the total area (hectares) of the kelp forest (Golding et al. 2019). This service value estimate will again be an underestimate of the total Falkland Islands resource, as it is based only on giant kelp which is visible on the surface of the water and not *Lessonia* spp. or deeper-water forest cover. The value per hectare also likely has a high range of uncertainty given the limited number of surveys on which the original replacement cost was based (Costanza et al. 1998).

Associated commercial fish stocks/harvests

We calculated average total fish catch (tonnes) over three years (2015-2017) for all 15 commercially-exploited fisheries within the Falkland Islands, based on government data (Falkland Islands Government 2018). We then selected the fisheries which are known to spawn, feed, or be resident during any part of their life-cycle within giant kelp habitats in the Falkland Islands. Limited data is available on trophic links, population distribution, ontogenetic habitat use, and life-history traits for many of these species. We therefore assume that any kelp habitat or near-kelp habitat utilisation of this type at any life-cycle stage is essential for sustaining the whole commercial fishery's population. Similarly, we only include fisheries directly observed within the kelp, excluding the other fisheries which may be found to have indirect trophic links and bio-physical influences from kelp systems.

We use the market value of each species (£GBP/metric tonne) to estimate the total value of the kelp system in terms of exploited kelp-associated fish harvest (Falkland Islands Government 2018). Values for embedded costs of running the fishery, such as salaries, fuel and equipment needs were unknown for these fisheries, preventing a 'value-added assessment' (i.e. revenue minus intermediate costs). Government revenue from fishery licence fees for all fisheries associated with the kelp system were averaged over a three-year period. For licences A, G and W (Suppl. material 1B), which are a mixture of restricted and unrestricted finfish, the licence fees are summarised for the nine relevant target species. Therefore the percentage of each category made up of each target species in 2017 landings was multiplied by the total licence income (Suppl. material 1C).

Alginate production

We use a non-use valuation technique, based on a historic alginate extraction pilot project in the Falkland Islands. A test plant was established in the 1970s (Shackleton 1976) and an economic study in the 1980s proposed obtaining a licence to harvest kelp at a minimum annual wet tonnage of 350,000 tonnes. World economic recession, global competition, and a shift of textile manufacturing to low-income countries, had caused the collapse of the textile market for alginates at that time for the UK (Shackleton 1982). We use this historic theoretical production level to contextualise the likely income from this resource if it were to be utilised in the Falkland Islands currently.

As no export industry currently exists, and given the proximity of the Falkland Islands to Chile, we assume the same export value per dry tonne for harvested kelps. Average export price of dry *Lessonia* spp. kelp out of Chile in 2009 for the alginate industry was US$ 950 per tonne (Bixler and Porse 2011). This equates to £917 per tonne, accounting for inflation and currency conversion to the present year.

Results

Modelling outputs using remote sensing data gave an estimated total coverage of kelp forest surrounding the Falkland Islands of 830.1 km^2 in 2019 (Fig. 1).

Carbon storage

Overall values of *Macrocystis pyrifera* density were highly variable, ranging between ~ 0.02 and 2.75 thalli/m^2 across all surveys, with a mean value of 0.293 thalli/m^2 (SE = ± 0.051) in spring, averaged across all years. Autumn density values were similar at 0.249 thalli/m^2 (SE = ± 0.039) averaged across all years. Overall values of *Lessonia* spp. density were again highly variable, ranging between 0.025 and 4.4 thali (whole plants)/m^2 across all surveys, with a mean value of 0.642 thalli/m^2 (SE = ± 0.069) in spring, averaged across all years. Autumn density values were 0.716 thalli/m^2 (SE = ± 0.082) averaged across all years.

The above seasonal density values resulted in an average of 0.12 million tonnes of CO_2e estimated to be stored in standing *M. pyrifera* vegetation, with a spring peak density equivalent to 0.21 million tonnes CO_2e. The average overall CO_2 stored by *Lessonia* spp. in the Falkland Islands is 0.30 million tonnes of CO_2e in spring and 0.37 million tonnes of CO_2e in autumn, assuming an equal proportion of *L. flavicans* and *L. trabeculata* within all surveys. Total seasonal CO_2e stored by standing kelp plants across the Falkland Islands (within the aerially-mapped extent) and respective biomass values are shown in Table 1.

Table 1.

Published values of total thallus wet and dry weight, mean population density, and carbon content for *Lessonia flavicans*, *L. trabeculata* and *Macrocystis pyrifera*. * *M. pyrifera* values based on estimations by Reed & Bzezinski (2009). † *M. pyrifera* values adapted from van Tussenbroek (1993), *Lessonia* spp. values adapted from Tala & Edding (2007). Total stored carbon estimated over the 831 km^2 mapped Falkland Island extent. Density values based on overall density of *Lessonia* spp. from 2008-2016 assuming a 50% split of species types.

Kelp characteristic	***Lessonia flavicans***		***Lessonia trabeculata***		***Macrocystis pyrifera***	
	Spring	Autumn	Spring	Autumn	Spring	Autumn
Typical population density (plants per m^2)†	6 ±1	8 ± 3	5 ± 2	5 ± 2	0.62	0.72
Plant biomass wet weight (kg m^{-2}) †	12 ±3	12 ± 4	17 ± 4	21 ± 2	8.0	1.4
Plant biomass dry weight (kg m^{-2}) †	1.62 ±0.44	2.23 ± 0.60	4.55 ± 1.05	5.78 ± 0.75	0.8	0.14
Dry weight per plant (kg) †	0.27 ± 0.04	0.29 ± 0.12	1.04 ± 0.47	1.28 ± 0.40	1.29	0.19
Dry weight as percentage of wet weight (per plant, i.e. holdfast, stipe, and blades)*	13.7	18.3	26.6	26.0	10.0	10.0
Percentage C g^{-1} dry weight†	27.23 ±1.07	23.44 ± 1.92	22.32 ± 0.69	21.21 ± 0.75	30.0	30.0
Average surveyed density from 2008-2016 (plants m^{-2})	0.64	0.72	0.64	0.72	0.29	0.25
Average amount of Carbon (kg m^{-2})*	0.05	0.05	0.15	0.19	0.07	0.01
Total carbon (tonnes)	39,180	40,401	123,705	161,357	57,774	8,716
Total CO_2e (tonnes)	**143,662**	**148,137**	**453,583**	**591,641**	**211,838**	**31,958**

Applying the mean productivity value of 985 g C m^{-2} yr^{-1} (Reed and Bzezinski 2009), and the estimated percentage of DOC and POC sequestered to deep sea (Krause-Jensen and Duarte 2016), the average carbon sequestration value for the Falkland Islands is 0.081 Tg carbon $year^{-1}$. This is equivalent to 0.299 million tonnes of CO_2, as shown (with corresponding maximum and minimum estimates) in Table 2.

Table 2.

Rounded minimum, average, and maximum estimated values of carbon sequestered from the Falkland Islands kelp forests per year, based on current known distribution and NPP rates of 670-1300 g C m^{-2} yr^{-1}.

Sequestration route	**Carbon $year^{-1}$**		
	Minimum	Average	Maximum
POC buried in shelf (Tg)	0.005	0.007	0.009
POC exported to deep sea (Tg)	0.013	0.019	0.025
DOC exported below the mixed layer (Tg)	0.038	0.056	0.074
Total sequestered blue carbon (Tg)	0.055	0.081	0.107
Total sequestered CO_2 (million tonnes)	0.203	0.299	0.3945

The combined total peak estimate of CO_2 equivalent carbon stored in standing giant and understorey kelp species within the satellite-derived mapped extent of kelp forest in the Falkland Islands is 0.58 million tonnes. Averaged (central estimate) total sequestration to the deep sea is 0.299 million tonnes of CO_2 annually. Based on non-traded high-series carbon dioxide equivalent (CO_2e) values (BEIS 2019), of £103.9 per tonne CO_2e, present-day standing stock of carbon stored in *Macrocystis* and *Lessonia* kelp is equivalent to £60.27 million. The annual value of carbon sequestered to deep sea sediments is estimated to be approximately £31.07 million per year.

Table 3.

Indirect value calculations for the nutrient-cycling benefit of Falkland Island kelp systems, based on remote-sensed total area. USD = United States Dollars, GBP = Great British Pounds.

Value parameters	**Indirect value**
Total area of kelp (Falkland Islands)	830 Km^2
Total area of kelp (Falkland Islands)	83,009 Ha
Value of nutrient cycling of seagrass / algae beds (based on 2011 values in USD ha^{-1}, from Costanza et al. (2014), Costanza et al. (1998))	\$28,916.00 ha^{-1} $year^{-1}$
Total value in 2007 USD yr^{-1} (based on Costanza et al. (2014)) for the Falkland Islands	\$2.40 Billion $year^{-1}$
Conversion from 2007 USD to 2020 USD with inflation (1\$ = 1.25\$)	\$3.00 Billion $year^{-1}$
Total value (conversion from USD to GBP at 0.8)	**£2.40 Billion $year^{-1}$**

Nutrient cycling

Coastal algae and seagrass beds were collectively estimated by Costanza et al. (2014) to contribute \$28,916 USD per hectare per year in terms of nutrient cycling services alone as of 2011 (based on the 2007 USD purchasing power parity). Applying these global values, the Falkland Islands are likely to contribute a total of £2.4 billion per year, based on remote-sensed kelp distribution (Table 3).

Associated commercial fisheries

Six of the 15 major fisheries within the Falkland Islands were found to be reliant on kelp for some period of their life-cycle, based on current knowledge. This includes the kingclip (*Genypterus blacodes*), Patagonian scallop (*Zygochlamys patagonica*), Patagonian squid (*Doryteuthis gahi*), Red cod (*Salilota australis*), Rock cod (*Patagonotothen* spp.), and Southern blue whiting (*Micromesistius australis*). Collectively, these fisheries total an annual harvest value of £129,291,813 (~ 24% of the total commercial fishery harvest value), and £7,049,575 in licence fees (equivalent to ~ 36% of the total licence revenue) for the Falkland Islands (Table 4).

Table 4.

Commercial fisheries of the Falkland Islands (2019/2020). Detailing residency or spawning within Falkland Island kelp systems, 3-year averaged total catch (tonnes), value (sterling) and total annual revenue per species for harvest and licence fees. Kelp-associated species shown in bold with greyed background (* Only a proportion of population, ** only as adults, *** only as larvae).

Common name	**Scientific name**	**Code (FAO)**	**Resident in kelp forest**	**Spawning within kelp**	**Total catch (tonnes) Avg 15-17**	**Value (£/mt)**	**Total harvest value**	**License revenue**
Kingclip (Cusk-eel)	*Genypterus blacodes*	CUS	**Yes**	No	2,076	1,438	2,984,809	183,724
Patagonian scallop	*Zygochlamys patagonica*	ZYP	**Yes** *	**Yes**	4	2,000	8,667	0
Patagonian squid (Falkland Calamari / Loligo)	*Doryteuthis gahi*	SQP	**Yes**	**Yes** *	47,149	2,500	117,871,667	6,375,312
Red cod	*Salilota australis*	SAO	**Yes** **	No	2,620	405	1,061,235	146,197
Rock cod (mix species)	*Patagonotothen* spp	PAT	**Yes** ***	**Yes**	12,882	405	5,217,075	64,753
Southern blue whiting	*Micromesistius australis*	POS	**Yes** ***	No	3,505	613	2,148,361	279,589
Austral hake	*Merluccius* spp / *australis*	HKX / HKN	No	No	238	2,182	520,043	0

Common name	Scientific name	Code (FAO)	Resident in kelp forest	Spawning within kelp	Total catch (tonnes) Avg 15-17	Value (£/mt)	Total harvest value	License revenue
Common hake	*Merluccius hubbsi*	HKP	No	No	19,996	787	15,736,590	1,427,455
Grenadier sp	*Macrouridae*	RTX	No	No	1,992	617	1,228,858	448,415
Hoki (whiptail hake / blue genadier)	*Macruronus magellanicus*	GRM	No	No	7,487	537	4,020,340	465,414
Illex argentinus (Argentine squid)	*Illex argentinus*	SQA	No	No	142,523	2,550	363,484,958	8,549,411
Martialia (squid)	*Martialia hyadesi*	SQS	No	No	0	1,170	0	0
Patagonian toothfish	*Dissostichus eleginoides*	TOP	No	No	1,415	11,456	16,210,240	836,770
Skates and rays	*Rajidae*	SRX	No	No	5,163	900	4,646,400	247,121
Other	*Osteichthyes/ Chondrichthyes*	MZZ/ SKX	No	No	345	613	211,485	360,944
Total					247,393	28,173	535,350,727	19,385,105
Total value (kelp associated fisheries)							**129,291,813**	**7,049,575**

It is important to highlight that while kelp provides habitat directly to these species, the biological and oceanographic influence of kelp to the nearshore environment will also trigger potentially large indirect effects on a range of other species, through trophic links which we are unable to assess fully here.

Alginate extraction

Based on the Shackleton (1982) theoretical estimates of the Falkland Islands' viable annual wet tonnage extraction of 350,000 tonnes (i.e. ~ 5% of the Falkland Islands' kelp area impacted), the total dry weight of kelp for export would be approximately 70,000 tonnes, (assuming *Lessonia* spp. dry weight as 20% of wet weight). Applying the Chilean export value of £917 tonne^{-1} would lead to a (non-use) revenue value of £64.19 million

$year^{-1}$. In the initial Shackleton (1982) economic assessment, Falkland Islands Government (FIG) would receive licence royalties, which would be equivalent to ~ £147,057 $year^{-1}$ in present value after inflation.

Cumulative value of assessed kelp services

Table 5 displays a summary of annual and spatial value estimates for all services investigated during this study. Values for other services including tourism, scientific research, culture, and coastal protection are still currently unknown or data-limited in this region, and are therefore not included within the summary.

Table 5.

Summary value estimates of services associated with giant kelp forest in the Falkland Islands in 2020. Overall remotely-mapped kelp extent for spatial estimates = 830.1 km^2. * Blue carbon stock value given assuming the standing stock protected over ten years and applying the future projected CO_2e value. Full values for tourism, scientific research, culture, and coastal protection are still currently data-limited or unknown.

Service	**Value estimate (£GBP $year^{-1}$)**	**Spatial value estimate (£GBP km^{-2} $year^{-1}$)**
Blue carbon stock	0.703 million*	84,721
Blue carbon sequestration	31.07 million	37,436
Nutrient cycling	2,400.29 million	2.89 million
Associated commercial fisheries value	126.3 million	152,177
Alginate industry (non-use)	64.19 million	77,337
TOTAL	**2,692.17 million**	**3.24 million**

Discussion

The total estimated value of the assessed ecosystem services which are provided by the Falkland Islands' satellite-mapped kelp forests in 2020, was ~ £2.692 billion per year (or £3.24 million GBP km^{-2} $year^{-1}$). This overall monetary value is constructed using estimated values of both direct and indirect services provided by the kelp system as a whole. Indirect services included atmospheric carbon stored or sequestered to the deep sea by *Macrocystis pyrifera* and *Lessonia* kelps, as well as nutrients which are fixed or recycled within the kelp forests. Direct services included the harvest value of kelp-associated commercial fisheries and the theoretical harvest value of the kelp itself for alginate chemicals used in industry. Despite the differences created by ecosystem service valuations in different locations around the world, our estimates of total value are comparable to other studies that attempted complete economic valuation of giant kelp forests elsewhere (Blamey and Bolton 2018, Vásquez et al. 2014). Blamey and Bolton (2018) found kelp systems in South Africa to be worth $434 million USD $year^{-1}$ over 50 km^2

(or £5.57 million GBP year^{-1} km^{-2}). Vásquez et al. (2014) valued the kelp in northern Chile at $541 million USD over 135 km^2 (or £2.57 million GBP km^{-2}). Accounting for the far larger size of the Falkland Islands' kelp system, at an estimated extent of 830 km^2, the service value estimates are at a comparable level. The present study provides the first quantified basis for development of contemporary kelp management strategies on the Patagonian Shelf, as well as a value to form a basis from which future estimates can be made under various climate change scenarios.

Nutrient cycling was found to be the most valuable service provided by the kelp ecosystem in terms of monetary value. However, values used to estimate nutrient cycling were not Falkland Islands specific, but rather integrated a broad range of estimates calculated for a range of global habitats (including tropical seagrass) (Costanza et al. 1998). Hence, the value of nutrient cycling should be interpreted with caution, as cycling capacity varies according to both: biotic factors, i.e. macrophyte species type, age, and associated biodiversity (Peters et al. 2019, Roleda and Hurd 2019); and abiotic factors, i.e. water temperature, light, salinity, and movement (Pfister et al. 2019, Roleda and Hurd 2019). As a consequence, more location and species-specific data are needed to accurately parameterise this ecosystem service estimate.

After nutrient cycling, the next most valuable service was provided by the fisheries and then the climate-buffering service of carbon sequestration. As expected, carbon standing stock value was quite low relative to the other services (based on current CO_2e values), with the total value cycling up and down again seasonally through the year as the kelp grows and dies-back (Vásquez et al. 2014, Graham et al. 2007). Over time, the overall value of this carbon storage service will increase, in line with the increase in trading values of market-based carbon credits.

Applications for kelp management

Carbon storage

In terms of the climate buffering benefit from carbon capture, the study showed that the Falkland Islands likely sequesters 0.299 million tonnes of CO_2 annually (at a conservative minimum estimate). This amount represents an additional annual contribution of approximately 0.1% of current UK net emissions (364.1 million tonnes CO_2e/year in 2018) towards their Nationally Determined Contribution (NDC) legally committed to through the Paris Agreement. UK's current NDC commitment is a reduction of 61% from 1990 baseline levels of ~ 601 million tonnes CO_2e per year, by 2030 (www.gov.uk). While the contribution from Falkland Islands kelp is relatively small, this is a year-on-year national-scale positive benefit from simply maintaining the natural habitat at its current extent and condition, even applying our conservative estimates.

This element of the study would benefit from additional research in a number of areas. Firstly, it is important to have long-term data on the annual variation in the extent of kelp forests around the Falkland Islands to quantify trends in abundance and distribution (and the rate of change). More detailed analyses and predictions on depth and density/condition (health) of the kelp would also allow for improved estimates of total biomass and management. This study assumes a consistent density across the distribution and uses known biomass estimates from kelp collected at ~ 5 m only (van Tussenbroek 1993). It is therefore very likely that total biomass estimates are underestimated. Linked to this point, improved knowledge of individual species' average biomass by height, and Falkland Islands-specific total NPP values for kelp forest would help refine future analyses (Filbee-Dexter and Wernberg 2020).

Secondly, while smaller kelps such as *Lessonia* spp. were included in this analysis, their full extent is actually larger than that of *Macrocystis pyrifera. Lessonia* spp. exist in additional locations and at a range of depths. Improving our confidence in the full extent of *Lessonia* spp., along with the vertical extent of deeper-water kelps from all species (which are not visible from above the water), would improve management and likely increase the overall valuation amount significantly. Increased confidence in total distribution around the Falkland Islands, especially in deep waters, could potentially be achieved through collection of acoustic backscatter data to identify presence of vegetation (Kenny et al. 2003). Combining such data with in-water benthic surveys to allow species distribution modelling (Elith and Leathwick 2009) would also improve valuation estimates. Remote-sensed satellite data on wave exposure (i.e. from Sentinel-1 Radar), would further help to parametrise modelling, and allow informed predictions to be made of coastal protection services from kelp.

Thirdly, a missing element to this valuation study is in the quantification of the amount of carbon already sequestered to the deep sea sediments from the kelp forests over the last centuries. Given current estimates of sequestration rates, this value is likely to be substantial, which should be a consideration of any future deep-sea fishing/extraction/damaging activities in these deep highly-sedimented areas. It is also worth considering the potentially significant additional carbon added to the sequestration pathway through degraded phytoplankton, waste, and carbon immobilised within dead consumer's tissues (Bax et al. 2020), which we were unable to quantify within this study.

It is important to note that carbon valuation elements, such as the 'Social Cost of Carbon' (SCC) method used to create aspects of the non-market value, is essentially a construct that we as people have applied. Therefore, SCC incorporates a large amount of uncertainty, ethical judgements, political beliefs and regional variation. While SCC is very useful as a tool for conceptualising value and debating cost-benefits of a service for policy-making, it is not an absolute value, and so values will likely change over time as knowledge and perceptions change. Aligned with the variation in possible SCC values, other values which feed into the overall valuation of the carbon market, including the cost of oil, are also variable and are liable to become rapidly outdated.

Fisheries harvest

Licence fees from fisheries which are associated with the kelp forest systems amount to an average annual revenue of £7,049,575 to the Falkland Island Government or £8,493 km^{-2} of kelp. Within our study, we have only evaluated the harvested commercial catch.

Consequently, this estimate of the ecosystem provisioning service does not account for additional non-commercial or unharvested fish which are dependent on the system (which may sustain charismatic tourist-friendly species such as dolphins, penguins or sea lions). The harvest value is also changeable, based on market prices and catch quotas, and different fishery species may become commercially valuable in the future.

Data were limited on the proportion of the population of each fishery that is dependent on the kelp forests, and on the extent to which this habitat's presence and health will influence the continuation of the fishery. We assume here that, if any aspect of the fisheries' life-cycle is associated with or influenced by the kelp forest, the fishery is wholly reliant on the habitat, which may not be the case. Furthermore, we have limited information on the complete influence of the kelp inshore environment on surrounding adult or planktonic species, or a complete understanding of the likely complex trophic links which exist. Therefore, more fisheries may be indirectly linked to kelp and this is an area in need of further research.

Nutrient cycling

The greatest individual ecosystem service value comes from kelp's ability to recycle nutrients and clean coastal waters. Without appropriate management of kelp forest systems, this service may become degraded, lowering the overall water quality surrounding the coasts and reducing productivity in associated fisheries that utilise these nutrients (Bertocci et al. 2015, Beaton et al. 2020, Jiang et al. 2020, Pfister et al. 2019). The replacement cost of this regulation service through artificial processes would be extremely costly and inefficient. The reduction in water quality through increased turbulence and phytoplankton without kelp (Narayan et al. 2016, Gaylord et al. 2007, Pfister et al. 2019) and associated loss of biodiversity and function linked to kelp forest (Graham et al. 2007), would also likely have negative impacts for the tourism value of this area, through reduced underwater and beach aesthetics (González and Holtmann-Ahumada 2017).

Kelp harvest

If the hypothetical alginate industry were to be instigated in the Falkland Islands, an appropriate management strategy and impact evaluation would be necessary in order to harvest kelp sustainably. This would need to include research into the least damaging harvest times, the extent of impact it would cause, and the optimal method of extraction. Linked to any such work would be a cost-benefit analysis of how this activity would affect the other services shown in this work and the important associated biodiversity. Additionally, in a similar fashion to carbon market values, the market values of harvested kelp-associated fish and kelp itself for the alginate industry, can also rapidly change. This is demonstrated well in the 171% increase in the export value of *Lessonia*-derived alginate from 1999 to 2009 (Bixler and Porse 2011).

Kelp services for future analysis

Marine systems often hold important cultural, historical or religious values for people which live close to them and rely on their services for their livelihoods or well-being (Rodrigues Garcia et al. 2017, Martin et al. 2016). However, these services are complex to quantify in terms of monetary value and rely heavily on qualitative opinions of those people who directly interact with the coast or ocean, resulting in very limited current global information about coastal and marine cultural ecosystem services (Martin et al. 2016). There is currently a poor understanding of socio-ecological relationships in marine systems generally, limited indicators, and differing values which people assign to various systems worldwide. It is also notoriously hard to quantify and assign a monetary value to a particular habitat or location (Blake et al. 2017). Quantifying the value gained through the specific cultural services of the kelp system during this assessment was beyond the scope of the present study. However, these services are likely to be highly valuable per capita in the Falklands where the economy is largely based on a healthy marine ecosystem, and given existing broader-scale value assessments in the region (Bormpoudakis et al. 2019, Smith 2019). This difficulty in giving a monetary value for the cultural/spiritual services of ecosystems specifically, is perhaps rooted in our inability to quantify something that may in all regards be ‘priceless’ to many people. Added to this is the innate difficulty in trying to value any ecosystem in isolation from its surrounding ecosystems and the interacting species and processes, to which it is inextricably linked.

In a similar fashion to cultural services, nature-based tourism can bring significant revenue for coastal communities through visitor’s appreciation of an area’s beauty, history or recreation, alongside the associated hospitality businesses. Coral reefs, for instance, are thought to provide a value of nearly US$36 billion, or over 9% of all coastal tourism value in the world's coral reef countries (Spalding et al. 2017). Limited work has been done on the direct tourism value of kelp systems; however, locations with large kelp systems and existing tourism infrastructure, such as California and South Africa’s Cape, receive revenue because of this system, through divers and snorkellers, wildlife observers (i.e. whale or otter watching), and recreational sailors (Blamey and Bolton 2018, Loomis 2006, Viana et al. 2017). Valuations may also extend to restaurants, shops, and accommodation supporting these areas, but the values will vary considerably depending on the country, accessibility, and popularity of the location. Tourism in the Falklands (focused on wildlife viewing and historic sites) is valuable, with 57,496 cruise visitors and 1,884 land-based leisure tourists during 2017/18. While many of the species which are a focus of wildlife viewing tours depend on the kelp for their continued abundance, it is difficult to disaggregate reasons for tourist visits to one feature. Bearing this in mind and given the limited existing dive infrastructure, limited data, and remote nature of the Falkland Islands, we did not include this service in our analysis.

The coastal protection provided by natural systems such as coral reefs, mangroves, and seagrass is substantial, reducing wave heights by up to 71% and attenuating water flow (Narayan et al. 2016, Martínez et al. 2007). Valuation of the benefits of these systems is typically based on matching the equivalent costs of building man-made barriers and defences which would perform the same role. Or alternatively through the avoided costs of damage and repair to property, infrastructure or life, from coastal erosion, storm waves, or coastal flooding/saltwater-intrusion to crops or groundwater etc. (Barbier et al. 2011, Narayan et al. 2016). Dependent on the degree of infrastructure in place close to the coast, the population size, frequency/intensity of storms, and the economic wealth of the country affected, the monetary benefit of having natural systems buffering the weather can be substantial. However, again the very low population size (3,398 people) and low density (0.28 people km^{-2}) of the Falkland Islands, based on the 2016 census, means that the only two hubs of population and infrastructure are in the naturally sheltered capital of Stanley and the inland RAF military base. The majority of the population lives in these two locations, with the remainder spread widely around the archipelago in remote farm small-holdings. Additionally, while there has been some baseline work on local wave exposure, data are currently unavailable for all of the Falkland Islands. These factors mean that the monetary value of the extensive surrounding kelp forests in terms of storm damage mitigation is not yet possible to quantify and will likely be low/negligible for this remote island case study.

Finally, as kelp is a foundation species and ecosystem engineer, the ecological and functional role of this habitat and the species which rely on it has been the focus of much scientific research and monitoring. The habitat therefore has value in terms of creation of research grants, associated travel and subsistence expenses within local businesses, and broader value for society through the creation of knowledge. In the northern region of neighbouring Chile, the estimated annual investment, in terms of scientific and applied research, in their kelp systems was US $66,174 annually or US $25,957,253 projected over 10 years (Vásquez et al. 2014). The Falkland Islands are smaller and more geographically isolated; however, the kelp systems still attract researchers from across the world and contribute to the overall research agendas of multiple Falklands-based science organisations, such as the South Atlantic Environment Research Institute (SAERI), Falkland Islands Government, Falklands Conservation, and British Antarctic Survey. The kelp forests have also attracted visits by researchers from universities, institutes and museums across the world; including from the UK, USA, Chile, Portugal and New Zealand during the last 10 years alone. However, detailed data quantifying research grants and expenses relating specifically to kelp research were limited, again preventing the inclusion of this service within our present analysis.

Future change

The Falkland Islands' kelp system appears to be healthy and stable based on the data currently available. However, a great deal of uncertainty still exists over how this and other kelp habitats globally will fare into the future (Smale et al. 2013, Sutherland et al. 2020). In the 'state of the environment' and Biodiversity Framework reports produced by Falkland Islands Government (FIG Environmental Planning Department 2016, Otley et al. 2008), a number of risk factors are identified for kelp, which need to be appropriately managed to avoid any degradation (and subsequent loss of value) of this system. As is typical of many small island nations, high priority threats are from potential invasive species and biosecurity issues. Medium and low threats come from development (i.e. habitat conversion) in coastal regions, pollution, and potential oil spills from exploration and extraction in the region. Any unregulated fishing activities, potential increases in land-based nutrient flows from farming practices, and the potentially damaging effects of tourism also need to be managed. Overarching all of these threats are the potential direct and indirect effects associated with future climatic change (Krumhansl et al. 2016, Smale et al. 2019).

While the majority of the local threats can be managed, uncertainty associated with broader climate-induced impacts on kelp and its associated communities, is likely to be the highest concern over the coming years (Krumhansl et al. 2016, Peters et al. 2019). Kelp is, to some degree, resilient to acute temperature fluctuations (Reed et al. 2016). Depite this resilience, increases in storm occurrence, chronic temperature changes, and shifting of key associated species' range will all drive potentially detrimental changes to this habitat (Krumhansl et al. 2016, Pecl et al. 2017, Arafeh-Dalmau et al. 2019). Such environmental changes would most likely reduce both the total habitat extent and the habitat quality, thereby reducing the kelp's ability to sequester carbon, cycle nutrients and provide habitat around the Falkland Islands. Just as on the land, the appropriate management and assessment of the carbon currently held within marine systems and their ability to sequester more, is an important component of mitigating climate change through reduction of emissions. Over the short-term, to maintain ecosystem service benefits and limit localised threats, sustained local management and monitoring of condition are needed (Macreadie et al. 2017b, Krumhansl et al. 2016). Furthermore, adaptations of existing management frameworks similar to the UN REDD+ (Reducing Emissions from Deforestation and forest Degradation) scheme for terrestrial forests might usefully be applied. Good marine and coastal management in this form will serve to protect not only the services directly utilised by humans, but also the important and abundant associated biodiversity supported by the kelp systems (Beaton et al. 2020, Duarte et al. 2020, Filbee-Dexter 2020).

While not directly valued in this study, biodiversity plays a key role in providing the basis of many ecosystem services. Large healthy systems which are highly biodiverse can therefore improve the value of services and the systems are more likely to be sustainable (Isbell et al. 2015). Kelp forest provides habitat both on the benthic floor and throughout the water column to a host of associated species, ranging from small invertebrates to large cetaceans (Beaton et al. 2020, Graham et al. 2007). More broadly, drifting kelp can provide important trophic and nutrient subsidies to beach communities (Lowman et al. 2019), as well as aid dispersal of sessile benthic fauna (Nikula et al. 2010). Kelp forest and its associated species therefore play important ecological roles for sustaining commercially-valuable species, as well as providing trophic pathways for a range of functional nearshore processes (Smale et al. 2013, Steneck et al. 2002). Aside from these direct values, diverse ecosystems are potentially important for humanity through the development of chemicals and medicines, and hold an inherent existence/bequest value to future generations (Smale et al. 2013, Filbee-Dexter 2020). While these functions and values can be extremely difficult to quantify monetarily, the continued maintenance and health of these systems and their associated species is an important factor to consider when judging ecosystem services and how to manage these into the future (Sanchirico and Mumby 2009, Nash et al. 2017).

Conclusion

This study illustrates that the Falkland Islands' kelp forests supply a range of valuable services to people, which are important both locally and globally. Thanks to the area's geographical isolation and low population, the kelp system currently appears healthy and stable. If future detrimental environmental changes, such as increased local pollution, introduction of unsustainable fisheries, or rapid temperature rise were to occur, we would expect to see declines in terms of habitat distribution and condition. If the system were to decline on a large scale, the loss of direct ecosystem service benefits to the Falkland Islands and the loss of wider benefits to the world through its indirect services, would be substantial and costly. Close monitoring of habitat extent and active management of local stressors will be key to the long term stability of the system, and ensure continued flow of multiple ecosystems services to society.

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References

- Arafeh-Dalmau N, Montaño-Moctezuma G, Martinez J, Beas-Luna R, Schoeman D, Torres-Moye G (2019) Extreme marine heatwaves alter kelp forest community near its equatorward distribution limit. Frontiers in Marine Science 6 (JUL): 1-18. https://doi.org/10.3389/fmars.2019.00499
- Barbier EB, Hacker SD, Kennedy C, Koch E, Stier AC, Silliman BR (2011) The value of estuarine and coastal ecosystem services. Ecological Monographs 81 (2): 169-193. https://doi.org/10.1890/10-1510.1
- Bax N, Sands C, Gogarty B, Downey R, Moreau CE, Moreno B, Held C, Paulsen M, McGee J, Haward M, Barnes DA (2020) Perspective: Increasing blue carbon around Antarctica is an ecosystem service of considerable societal and economic value worth protecting. Global Change Biology (April)1-8. https://doi.org/10.1111/gcb.15392
- Bayley DTI, Marengo I, Baker H, Pelembe T (2017) Giant kelp 'Blue carbon' storage and sequestration value in the Falkland Islands. South Atlantic Environment Institute, Falkland Islands. https://doi.org/10.13140/RG.2.2.31988.24966
- Beaton EC, Küpper FC, van West P, Brewin PE, Brickle P (2020) The influence of depth and season on the benthic communities of a Macrocystis pyrifera forest in the Falkland Islands. Polar Biology (0123456789). https://doi.org/10.1007/s00300-020-02662-x
- Beaumont NJ, Austen MC, Atkins JP, Burdon D, Degraer S, Dentinho TP, Derous S, Holm P, Horton T, van Ierland E, Marboe AH, Starkey DJ, Townsend M, Zarzycki T (2007) Identification, definition and quantification of goods and services provided by marine biodiversity: Implications for the ecosystem approach. Marine Pollution Bulletin 54 (3): 253-265. https://doi.org/10.1016/j.marpolbul.2006.12.003
- BEIS (2019) Valuation of energy use and greenhouse gas: Supplementary guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government. Department for Business, Energy and Industrial Strategy.
- Bertocci I, Araújo R, Oliveira P, Sousa-Pinto I (2015) REVIEW: Potential effects of kelp species on local fisheries. Journal of Applied Ecology 52 (5): 1216-1226. https://doi.org/10.1111/1365-2664.12483
- Bixler H, Porse H (2011) A decade of change in the seaweed hydrocolloids industry. Journal of Applied Phycology 23 (3): 321-335. https://doi.org/10.1007/s10811-010-9529-3
- Blake D, Augé A, Sherren K (2017) Participatory mapping to elicit cultural coastal values for Marine Spatial Planning in a remote archipelago. Ocean and Coastal Management 148: 195-203. https://doi.org/10.1016/j.ocecoaman.2017.08.010

- Blamey L, Bolton J (2018) The economic value of South African kelp forests and temperate reefs: Past, present and future. Journal of Marine Systems 188: 172-181. https://doi.org/10.1016/j.jmarsys.2017.06.003
- Bormpoudakis D, Fish R, Guest A, Smith N (2019) South Atlantic Natural Capital Assessment: Cultural Ecosystem Services in the Falkland Islands.
- Costanza R, D'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill R, Paruelo J, Raskin R, Sutton P, van den Belt M (1998) The value of the world's ecosystem services and natural capital. Nature 387 (6630): 253-260. https://doi.org/10.1038/387253a0
- Costanza R (1999) The ecological, economic, and social importance of the oceans. Ecological Economics 31: 199-213. https://doi.org/10.1016/S0921-8009(99)00079-8
- Costanza R, de Groot R, Sutton P, van der Ploeg S, Anderson S, Kubiszewski I, Farber S, Turner RK (2014) Changes in the global value of ecosystem services. Global Environmental Change 26 (1): 152-158. https://doi.org/10.1016/j.gloenvcha.2014.04.002
- DECC (2009) Carbon Valuation in UK Policy Appraisal: A Revised Approach. Department of Energy and Climate Change.
- Duarte C, Agusti S, Barbier E, Britten G, Castilla JC, Gattuso J, Fulweiler R, Hughes T, Knowlton N, Lovelock C, Lotze H, Predragovic M, Poloczanska E, Roberts C, Worm B (2020) Rebuilding marine life. Nature 580 (7801): 39-51. https://doi.org/10.1038/s41586-020-2146-7
- Elith J, Leathwick J (2009) Species distribution models: Ecological explanation and prediction across space and time. Annual Review of Ecology, Evolution, and Systematics 40 (1): 677-697. https://doi.org/10.1146/annurev.ecolsys.110308.120159
- European Commission (2020) Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions: EU Biodiversity Strategy for 2030 - Bringing nature back into our lives. Publications Office of the European Union, Luxembourg. [ISBN 9279207628]
- Falkland Islands Government (2018) Fisheries Statistics. FIG Fisheries Department 22: -100.
- FIG Environmental Planning Department (2016) Falkland Islands Biodiversity Framework.
- Filbee-Dexter K (2020) Ocean forests hold unique solutions to our current environmental crisis. One Earth 2 (5): 398-401. https://doi.org/10.1016/j.oneear.2020.05.004
- Filbee-Dexter K, Wernberg T (2020) Substantial blue carbon in overlooked Australian kelp forests. Scientific Reports 10 (1). https://doi.org/10.1038/s41598-020-69258-7
- Gaylord B, Rosman J, Reed D, Koseff J, Fram J, MacIntyre S, Arkema K, McDonald C, Brzezinski M, Largier J, Monismith S, Raimondi P, Mardian B (2007) Spatial patterns of flow and their modification within and around a giant kelp forest. Limnology and Oceanography 52 (5): 1838-1852. https://doi.org/10.4319/lo.2007.52.5.1838
- Golding N, Black B, Blake D, Brewin P, Harte M, Havercroft H, James R, Jones G (2019) Long-term coastal habitat mapping & monitoring handbook. Examples based on work undertaken in the Falkland Islands & South Georgia. DPLUS065 Coastal Habitat Mapping project.

- González S, Holtmann-Ahumada G (2017) Quality of tourist beaches of northern Chile: A first approach for ecosystem-based management. Ocean & Coastal Management 137: 154-164. https://doi.org/10.1016/j.ocecoaman.2016.12.022
- Graham MH, Vásquez JA, Buschmann AH (2007) Global ecology of the giant kelp macrocystis: From ecotypes to ecosystems. Oceanography and Marine Biology 45: 39-88.
- Haines-Young R, Potschin M (2013) Common International Classification of Ecosystem Services (CICES): Consultation on Version 4. https://doi.org/10.1038/nature10650
- Himes-Cornell A, Pendleton L, Atiyah P (2018) Valuing ecosystem services from blue forests: A systematic review of the valuation of salt marshes, sea grass beds and mangrove forests. Ecosystem Services 30: 36-48. https://doi.org/10.1016/j.ecoser.2018.01.006
- Isbell F, Tilman D, Polasky S, Loreau M (2015) The biodiversity-dependent ecosystem service debt. Ecology Letters 18 (2): 119-134. https://doi.org/10.1111/ele.12393
- Jiang Z, Liu J, Li S, Chen Y, Du P, Zhu Y, Liao Y, Chen Q, Shou L, Yan X, Zeng J, Chen J (2020) Kelp cultivation effectively improves water quality and regulates phytoplankton community in a turbid, highly eutrophic bay. Science of the Total Environment 707 https://doi.org/10.1016/j.scitotenv.2019.135561
- Jones KR, Klein CJ, Halpern BS, Friedlander AM, Possingham HP, Watson JEM (2018) The location and protection status of Earth's diminishing marine wilderness. Current Biology 28: 1-7. https://doi.org/10.1016/j.cub.2018.06.010
- Kenny A, Cato I, Desprez M, Fader G, Schuttenhelm R, Side J (2003) An overview of seabed-mapping technologies in the context of marine habitat classification. ICES Journal of Marine Science 60 (2): 411-418. https://doi.org/10.1016/S1054-3139(03)00006-7
- Krause-Jensen D, Duarte C (2016) Substantial role of macroalgae in marine carbon sequestration. Nature Geoscience 9 (10): 737-742. https://doi.org/10.1038/ngeo2790
- Krumhansl KA, Okamoto DK, Rassweiler A, Novak M, Bolton JJ, Cavanaugh KC, Connell SD, Johnson CR, Konar B, Ling SD, Micheli F, Norderhaug KM, Pérez-Matus A, Sousa-Pinto I, Reed DC, Salomon AK, Shears NT, Wernberg T, Anderson RJ, Barrett NS, Buschmann AH, Carr MH, Caselle JE, Derrien-Courtel S, Edgar GJ, Edwards M, Estes JA, Goodwin C, Kenner MC, Kushner DJ, Moy FE, Nunn J, Steneck RS, Vásquez J, Watson J, Witman JD, Byrnes JEK (2016) Global patterns of kelp forest change over the past half-century. Proceedings of the National Academy of Sciences of the United States of America 113 (48): 13785-13790. https://doi.org/10.1073/pnas.1606102113
- Loomis J (2006) Estimating recreation and existence values of sea otter expansion in California using benefit transfer. Coastal Management 34 (4): 387-404. https://doi.org/10.1080/08920750600860282
- Lowman H, Emery K, Kubler-Dudgeon L, Dugan J, Melack J (2019) Contribution of macroalgal wrack consumers to dissolved inorganic nitrogen concentrations in intertidal pore waters of sandy beaches. Estuarine, Coastal and Shelf Science 219 (September 2018): 363-371. https://doi.org/10.1016/j.ecss.2019.02.004
- Macreadie P, Jarvis J, Trevathan-Tackett S, Bellgrove A (2017a) Seagrasses and macroalgae: Importance, vulnerability and impacts. In: Philips BF, Pérez-Ramírez M (Eds) Climate Change Impacts on Fisheries and Aquaculture. John Wiley & Sons, Ltd, Chichester, UK, 41 pp. [ISBN 9781119154051]. https://doi.org/10.1002/9781119154051.ch22

- Macreadie P, Nielsen D, Kelleway J, Atwood T, Seymour J, Petrou K, Connolly R, Thomson AC, Trevathan-Tackett S, Ralph P (2017b) Can we manage coastal ecosystems to sequester more blue carbon? Frontiers in Ecology and the Environment 15 (4): 206-213. https://doi.org/10.1002/fee.1484
- Maes J, Egoh B, Willemen L, Liquete C, Vihervaara P, Schägner JP, Grizzetti B, Drakou E, Notte AL, Zulian G, Bouraoui F, Luisa Paracchini M, Braat L, Bidoglio G (2012) Mapping ecosystem services for policy support and decision making in the European Union. Ecosystem Services 1 (1): 31-39. https://doi.org/10.1016/j.ecoser.2012.06.004
- Martin C, Momtaz S, Gaston T, Moltschaniwskyj N (2016) A systematic quantitative review of coastal and marine cultural ecosystem services: Current status and future research. Marine Policy 74: 25-32. https://doi.org/10.1016/j.marpol.2016.09.004
- Martínez ML, Intralawan A, Vázquez G, Pérez-Maqueo O, Sutton P, Landgrave R (2007) The coasts of our world: Ecological, economic and social importance. Ecological Economics 63 (2-3): 254-272. https://doi.org/10.1016/j.ecolecon.2006.10.022
- MEA (2005) Millenium Ecosystem Assessment. Ecosystems and Human Well-being: Synthesis. Island Press.
- Narayan S, Beck M, Reguero B, Losada I, Van Wesenbeeck B, Pontee N, Sanchirico J, Ingram JC, Lange GM, Burks-Copes K (2016) The effectiveness, costs and coastal protection benefits of natural and nature-based defences. PLoS ONE 11 (5): 1-17. https://doi.org/10.1371/journal.pone.0154735
- Nash K, Cvitanovic C, Fulton E, Halpern B, Milner-Gulland EJ, Watson R, Blanchard J (2017) Planetary boundaries for a blue planet. Nature Ecology & Evolution 1 (11): 1625-1634. https://doi.org/10.1038/s41559-017-0319-z
- Nikula R, Fraser CI, Spencer HG, Waters JM (2010) Circumpolar dispersal by rafting in two subantarctic kelp-dwelling crustaceans. Marine Ecology Progress Series 405: 221-230. https://doi.org/10.3354/meps08523
- Otley H, Munro G, Clausen A, Ingham B (2008) Falkland Islands State of the Environment Report, Falkland Islands Government and Falklands Conservation.
- Pecl G, Araújo M, Bell J, Blanchard J, Bonebrake T, Chen I, Clark T, Colwell R, Danielsen F, Evengård B, Falconi L, Ferrier S, Frusher S, Garcia R, Griffis R, Hobday A, Janion-Scheepers C, Jarzyna M, Jennings S, Lenoir J, Linnetved H, Martin V, McCormack P, McDonald J, Mitchell N, Mustonen T, Pandolfi J, Pettorelli N, Popova E, Robinson S, Scheffers B, Shaw J, Sorte CB, Strugnell J, Sunday J, Tuanmu M, Vergés A, Villanueva C, Wernberg T, Wapstra E, Williams S (2017) Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science 355 (6332). https://doi.org/10.1126/science.aai9214
- Peters J, Reed D, Burkepile D (2019) Climate and fishing drive regime shifts in consumer-mediated nutrient cycling in kelp forests. Global Change Biology 25 (9): 3179-3192. https://doi.org/10.1111/gcb.14706
- Pfister C, Altabet M, Weigel B (2019) Kelp beds and their local effects on seawater chemistry, productivity, and microbial communities. Ecology 100 (10): 1-15. https://doi.org/10.1002/ecy.2798
- Queirós AM, Stephens N, Widdicombe S, Tait K, McCoy S, Ingels J, Rühl S, Airs R, Beesley A, Carnovale G, Cazenave P, Dashfield S, Hua E, Jones M, Lindeque P, McNeill C, Nunes J, Parry H, Pascoe C, Widdicombe C, Smyth T, Atkinson A, Krause-Jensen D, Somerfield P (2019) Connected macroalgal-sediment systems: blue carbon

and food webs in the deep coastal ocean. Ecological Monographs 89 (3): 1-21. https://doi.org/10.1002/ecm.1366
- Reed D, Washburn L, Rassweiler A, Miller R, Bell T, Harrer S (2016) Extreme warming challenges sentinel status of kelp forests as indicators of climate change. Nature Communications 7 (1). https://doi.org/10.1038/ncomms13757
- Reed DC, Bzezinski MA (2009) Kelp Forests. In: Laffoley Dd, Grimsditch G (Eds) The management of natural coastal carbon sinks. IUCN, Gland, Switzerland. [ISBN 0160-8347]. https://doi.org/10.1007/s00114-001-0283-x
- Rodrigues Garcia J, Conides A, Rodriguez Rivero S, Raicevich S, Pita P, Kleisner K, Pita C, Lopes PM, Roldán Alonso V, Ramos S, Klaoudatos D, Outeiro L, Armstrong C, Teneva L, Stefanski S, Böhnke-Henrichs A, Kruse M, Lillebø A, Bennett E, Belgrano A, Murillas A, Pinto Sousa I, Burkhard B, Villasante S (2017) Marine and coastal cultural ecosystem services: Knowledge gaps and research priorities. One Ecosystem 2 https://doi.org/10.3897/oneeco.2.e12290
- Roleda M, Hurd C (2019) Seaweed nutrient physiology: application of concepts to aquaculture and bioremediation. Phycologia 58 (5): 552-562. https://doi.org/10.1080/00318884.2019.1622920
- Sanchirico J, Mumby P (2009) Mapping ecosystem functions to the valuation of ecosystem services: Implications of species-habitat associations for coastal land-use decisions. Theoretical Ecology 2: 67-77. https://doi.org/10.1007/s12080-008-0034-0
- Shackleton E (1976) Economic Survey of the Falkland Islands: Resources and Development Potential. Foreign and Commonwealth Affairs Report.
- Shackleton E (1982) Falkland Islands Economic study. Foreign and Commonwealth Affairs Report.
- Smale D, Burrows M, Moore P, O'Connor N, Hawkins S (2013) Threats and knowledge gaps for ecosystem services provided by kelp forests: A northeast Atlantic perspective. Ecology and Evolution 3 (11): 4016-4038. https://doi.org/10.1002/ece3.774
- Smale D, Wernberg T, Oliver EJ, Thomsen M, Harvey B, Straub S, Burrows M, Alexander L, Benthuysen J, Donat M, Feng M, Hobday A, Holbrook N, Perkins-Kirkpatrick S, Scannell H, Sen Gupta A, Payne B, Moore P (2019) Marine heatwaves threaten global biodiversity and the provision of ecosystem services. Nature Climate Change 9 (4): 306-312. https://doi.org/10.1038/s41558-019-0412-1
- Smith N (2019) Understanding the value of land based tourists in the Falkland Islands. South Atlantic Overseas Territories Natural Capital Assessment.
- Spalding M, Burke L, Wood SA, Ashpole J, Hutchison J, zu Ermgassen P (2017) Mapping the global value and distribution of coral reef tourism. Marine Policy 82 (May): 104-113. https://doi.org/10.1016/j.marpol.2017.05.014
- Steneck R, Graham M, Bourque B, Corbett D, Erlandson J, Estes J, Tegner M (2002) Kelp forest ecosystems: biodiversity, stability, resilience and future. Environmental Conservation 29 (4): 436-459. https://doi.org/10.1017/S0376892902000322
- Sutherland W, Dias M, Dicks L, Doran H, Entwistle A, Fleishman E, Gibbons D, Hails R, Hughes A, Hughes J, Kelman R, Le Roux X, LeAnstey B, Lickorish F, Maggs L, Pearce-Higgins J, Peck L, Pettorelli N, Pretty J, Spalding M, Tonneijck F, Wentworth J, Thornton A (2020) A Horizon Scan of Emerging Global Biological Conservation Issues for 2020. Trends in Ecology & Evolution 35 (1): 81-90. https://doi.org/10.1016/j.tree.2019.10.010
- UNFCC (2015) The Paris Agreement to the United Nations Framework Convention on Climate Change.

- van Tussenbroek BL (1993) Plant and frond dynamics of the giant kelp, *Macrocystis pyrifera*, forming a fringing zone in the Falkland Islands. European Journal of Phycology 28 (March): 161-165. https://doi.org/10.1080/09670269300650251
- Vásquez J, Zuñiga S, Tala F, Piaget N, Rodríguez D, Vega JM (2014) Economic valuation of kelp forests in northern Chile: values of goods and services of the ecosystem. Journal of Applied Phycology 26 (2): 1081-1088. https://doi.org/10.1007/s10811-013-0173-6
- Viana D, Gornik K, Lin CC, McDonald G, Ng NR, Quigley C, Potoski M (2017) Recreational boaters value biodiversity: The case of the California Channel Islands National Marine Sanctuary. Marine Policy 81 (March): 91-97. https://doi.org/10.1016/j.marpol.2017.03.017

Supplementary material

Suppl. material 1: Supplementary file doi

Authors: Dan Bayley
Data type: Data audit
Brief description: Summarised data inputs, methods and limitations for each kelp ecosystem service assessed in the Falkland Islands. Additional details on fish licenCe and catch value for commercial Falkland Islands species.
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