Giant kelp 'Blue carbon' storage and sequestration value in the Falkland Islands

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Contents

Glossary of Terms

Blue carbon: Carbon that is captured and stored within the world's marine / coastal vegetation habitats and their surrounding marine sediments.

Green carbon: Carbon that is captured and stored within the world's terrestrial and marine photosynthetic vegetation and surrounding soils / sediments.

Carbon stock: The quantity of carbon stored in a system which has the capacity to accumulate or release carbon.

Carbon sink: A habitat (i.e. a forest), system (i.e. ocean), or other natural environment viewed in terms of its ability to absorb carbon dioxide from the atmosphere, (the antonym of carbon 'Source').

Carbon sequestration: A natural or artificial process by which carbon dioxide is removed from the atmosphere and held in solid or liquid form, typically for a prolonged period of time.

1. Introduction

1.1. Background

Coastal ecosystems around the world are known to provide a range of valuable ecosystem services to people, for instance through coastal protection, commercial food supply and recreation (Beaumont *et al.* 2007; Barbier *et al.* 2011). Within these services, the 'Blue carbon' which is captured and stored as standing biomass, or sequestered into sediments from coastal vegetation such as mangroves, marshes and seagrass (Pendleton *et al.* 2012), is gaining attention as a globally important climate regulating service ('Millenium Ecosystem Assessment' 2005). However, the importance of macro-algae such as kelp forests within Blue carbon assessments has been relatively overlooked, primarily due to current uncertainty over precise rates of deep sea sequestration (Duarte 2016). As the knowledge of macro-algae distribution, abundance and sequestration rate increases (Graham *et al.* 2007; Reed & Bzezinski 2009; Krause-Jensen & Duarte 2016) it is becoming clear that macro-algae's role in carbon storage is likely substantial. Current global sequestration estimates for all marine macro-algae are ~173 Teragrams Carbon yr^{-1} (with a range of 61–268 Tg C yr^{-1}), with the majority of this sequestration being facilitated through transport into the deep sea (Krause-Jensen & Duarte 2016).

1.2. Biology and Ecology of kelp

Kelp forests are mixed assemblages of brown algae from the Order Laminariales, found globally within rocky coastal marine systems in temperate regions, and also less commonly in sub-tropical and sub-Antarctic locations. The shallow rocky coastal waters of the Falkland Islands are dominated by a large and relatively undisturbed system of giant kelp forests (*Macrocystsis pyrifera*), as well as diverse kelp understorey (kelp park) which includes *Lessonia* and *Durvillaea* species (Van Tussenbroek 1993).

Giant kelp is found in both the Northern and Southern hemisphere and is the most widely distributed of the kelps. *Macrocystis* is typically the dominant component of the kelp assemblage where it occurs, and is a foundation habitat which provides a range of important ecological and socio-economic functions and services (Martínez *et al.* 2007). This habitat typically occurs between the low intertidal and around 25 m in depth, although some deeper populations are also known to occur to 60+ metres (Graham *et al.* 2007).

The morphology of the macroscopic sporophyte stage of their life-phase is highly variable according to their local environment, but typically consists of a large holdfast attached to the substrate, with a collection of stipes, laminae (fronds) and pneumatocysts (collectively known as a thallus) growing from the top, which can reach lengths of up to 45 metres and provide a floating canopy habitat (Steneck *et al.* 2002). Sporophytes are typically highly seasonal in their size and distribution density, with thinning of the habitat normally occurring during winter storms, followed by a period of regrowth and recruitment in the summer period of low wave activity (Graham *et al.* 2007). Individual sporophytes typically live between 1 and 7 years, and individual fronds (of which there can be up to 400), typically senesce after 6-8 months, demonstrating a rapid turnover of biomass, and high frond productivity rates of between 2 and 15 g C m^{-2} day^{-1} in shallow habitats (Graham *et al.* 2007).

Kelp forest provides habitat both on the benthic floor and throughout the water column to a host of associated species. The forests typically hold distinct communities within their holdfasts, mid-water fronds / stipes, and within the surface floating canopy, just as within the vertically stratified layers of forests on land (Graham *et al.* 2007). The kelp-associated species, which can be highly variable spatially and temporally (Ríos *et al.* 2007), range from the small sessile invertebrates such as bryozoans and hydroids which typically encrust the holdfast and surface of the kelp, to the mobile fish, urchins and crustaceans which utilise the food resource and shelter it provides. Birds, pinnipeds, large predatory fish, and cetaceans are also frequent users of this environmental resource, together making up a diverse and often abundant ecosystem (Graham *et al.* 2007).

1.3. Threats to kelp forests

Kelp forests are typically subject to a number of pressures from both human and natural sources. Local scale factors such as nitrate availability, turbidity and wave disturbance (Bell *et al.* 2015), as well as regional scale temperature conditions are the dominant environmental drivers of kelp biomass (Krumhansl *et al.* 2016).

While local scale processes appear to affect structure and extent of kelp most strongly, changes in climate are affecting kelp ecosystems in a number of ways. Extreme climate events such as heatwaves have been shown to cause significant reduction in kelp habitat abundance and associated shifts in community structure towards a depauperate state (Wernberg *et al.* 2012). In some regions of the world, '*tropicalization*' is now occurring whereby shifting water currents are facilitating range expansion of temperature-limited species, while also causing sub-optimal conditions for kelp growth and in some cases a complete ecosystem shift away from kelp habitat (Vergés *et al.* 2014). Over-fishing of kelp-associated species is exacerbating these changes in range limits, causing trophic cascade processes which can ultimately lead to deforestation of kelp (i.e. urchin 'barrens'), and reduced resilience to disturbance events (Steneck *et al.* 2002; Ling *et al.* 2009).

However, in contrast to many other kelp habitats across the world, which experience strong seasonal changes in structure, the *Macrocystis* populations within the Falkland Islands have been shown to be relatively stable throughout the year. The forests here appear to not experience the same strong winter storms that tend to reduce the frond biomass of kelp through wave action in other high latitude areas (Van Tussenbroek 1993). Furthermore, the relative remoteness of the islands has protected the habitat to some degree from commercial exploitation of kelp associated species, and from direct harvesting of the kelp itself, which occurs in a number of regions, such as California (Barilotti & Zertuche-Gonzalez 1990).

More broadly, a recent global study by (Krumhansl *et al.* 2016) showed large variation in kelp forest habitat cover over the last 50 years. The global yearly average of abundance change across 34 'ecoregions' (Spalding *et al.* 2007) was -0.018 yr^{-1}, with a high variability in magnitude and trajectory of change between ecoregions, ranging from – 0.18 to + 0.11 yr^{-1} (Figure 1).

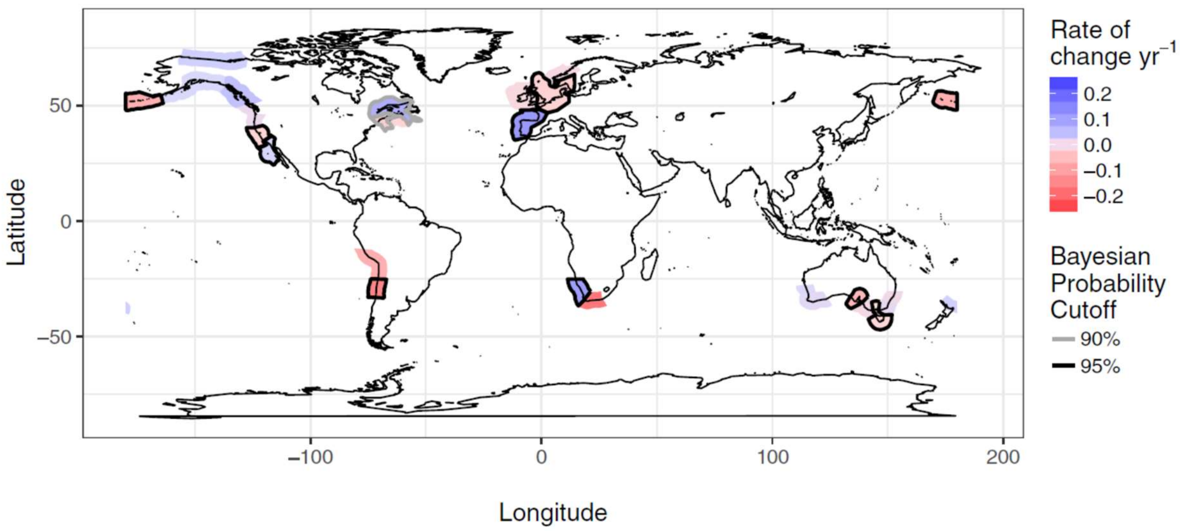

Figure 1. Illustrating the yearly rate of change and probability cut-off for kelp forests, from Bayesian modelled slopes of 26 ecoregions (sourced from (Krumhansl et al. 2016)).

1.4. Valuation of Blue carbon stocks

Ecosystem services

Ecosystem services are the benefits people obtain from ecosystems toward their overall well-being, and this concept encompasses the three broad categories of provisioning services (i.e. nutrition, water supply, materials, energy), regulating & maintenance services (i.e. regulation of biophysical environment, flow, physico-chemical and biotic environments), and cultural services (i.e. symbolic or intellectual and experiential) (Haines-Young & Potschin 2013).

Coastal ecosystems hold a range of goods and services important to people which fall within each of the defined service categories (Beaumont *et al.* 2007; Martínez *et al.* 2007). In order to appropriately value such services, Fisher *et al.* (2008) proposes a combination of the idea of ecosystem services with economics to assess the economic benefits derived from ecosystems through a number of metrics. This can be therefore be thought of as monetarily valuing ecosystems specifically according to their benefits to humans *i.e.* within the concept of 'Nature for people' (Mace 2014).

A common issue with any such valuations of ecosystems is in fully capturing a full and realistic total, as is attempted within the concept of Total Economic Valuation (TEV). This concept attempts this goal through the inclusion of not only the 'direct use' values, or 'goods', which are relatively easy to quantify, but also the '*in*direct use values' (the ecological functions / services), the future 'option use values', and the more abstract ideas of non-use 'bequest value' and 'existence value' (see Roy Haines-Young & Potschin (2013) for further details). This clear difficulty in giving a satisfactory monetary value for nature has led to strong debate over the last half century on how best to approach the problem, and gained particular attention following a global assessment by Costanza *et al.* (1997), in which they attempted to give a value to the world's services (Jacobs *et al.* 2016). The debate centres largely on the dichotomy between those who consider nature should be protected for its worth in relation to humans (instrumental value) or whether nature should be protected for its inherent value (intrinsic value), i.e. nature cannot be valued as it is essentially priceless (Tallis & Lubchenco 2014; Chan *et al.* 2016). At a more general level, the problems in finding consistent and meaningful values, especially for more indirect or abstract services has led to further contention and criticism, and is often deepened as frequent re-evaluations of ecosystems occur as more is learnt about their range of functions, i.e. (Pendleton *et al.* 2016).

Carbon sequestration

The removal and storage of atmospheric carbon dioxide through biological and chemical processes to 'sinks' such as oceans, soils or vegetation, is a natural part of the global carbon cycle and falls under the category of supplying in-direct use value to people through natural regulating services. The oceans are the largest of these natural sinks, and the waters of the high latitude areas around the Southern Ocean (including the areas surrounding the Falkland Islands), are known to have a negative overall annual net flux of CO_2 (Figure 2).

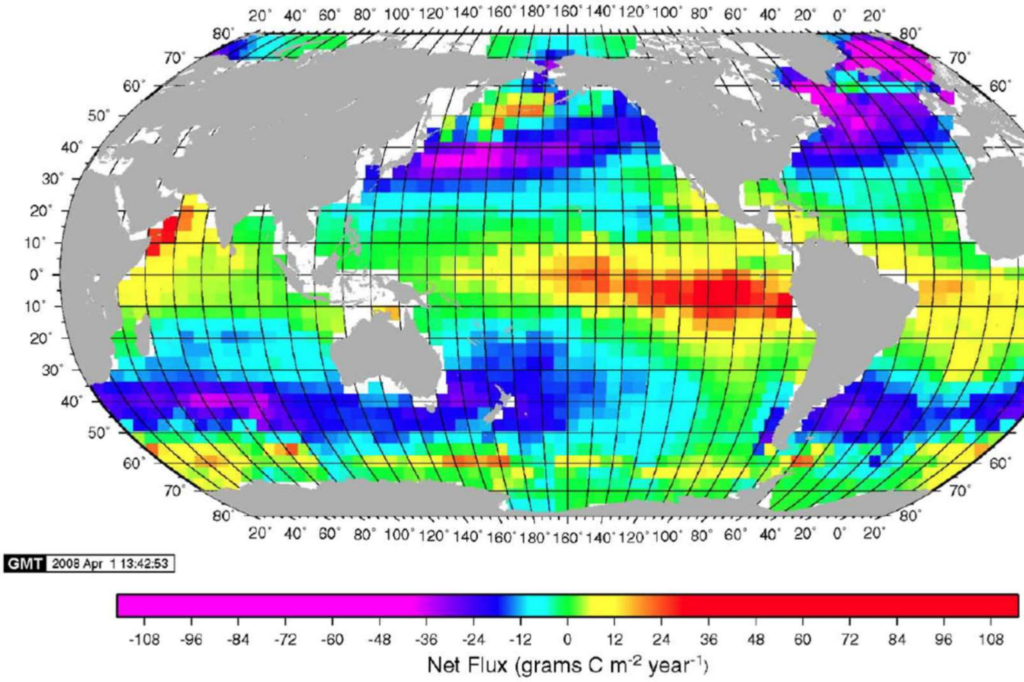

Figure 2. Global yearly net flux of Carbon m^{-2} within the oceans. Sourced from Takahashi *et al.* (2009).

'Blue carbon' is the term used explicitly for the carbon that is captured and stored (sequestered) within the world's marine and coastal habitats and sediments through removal of emissions from the atmosphere via living photosynthetic organisms. Habitats which have been found to yield large amounts of Blue carbon include seagrasses, tidal salt marshes, mangrove forest, and more recently, kelp forests (Laffoley & Grimsditch 2009). Blue carbon is a subset of 'Green carbon' (a term which also includes the world's terrestrial plants and soils), but it has until recently not garnered as much attention as a carbon 'sink', despite marine habitats capturing more overall carbon annually, and doing so more efficiently, than habitats on land (Nellemann *et al.* 2009; McLeod *et al.* 2011).

While kelp forests were previously thought to contribute little to sequestration of carbon (due to their habitat typically being located on hard rock as opposed to soft sediment), it is now clear that there is considerable potential for macro-algae to be sequestered to deep waters in a number of ways (Figure 3).

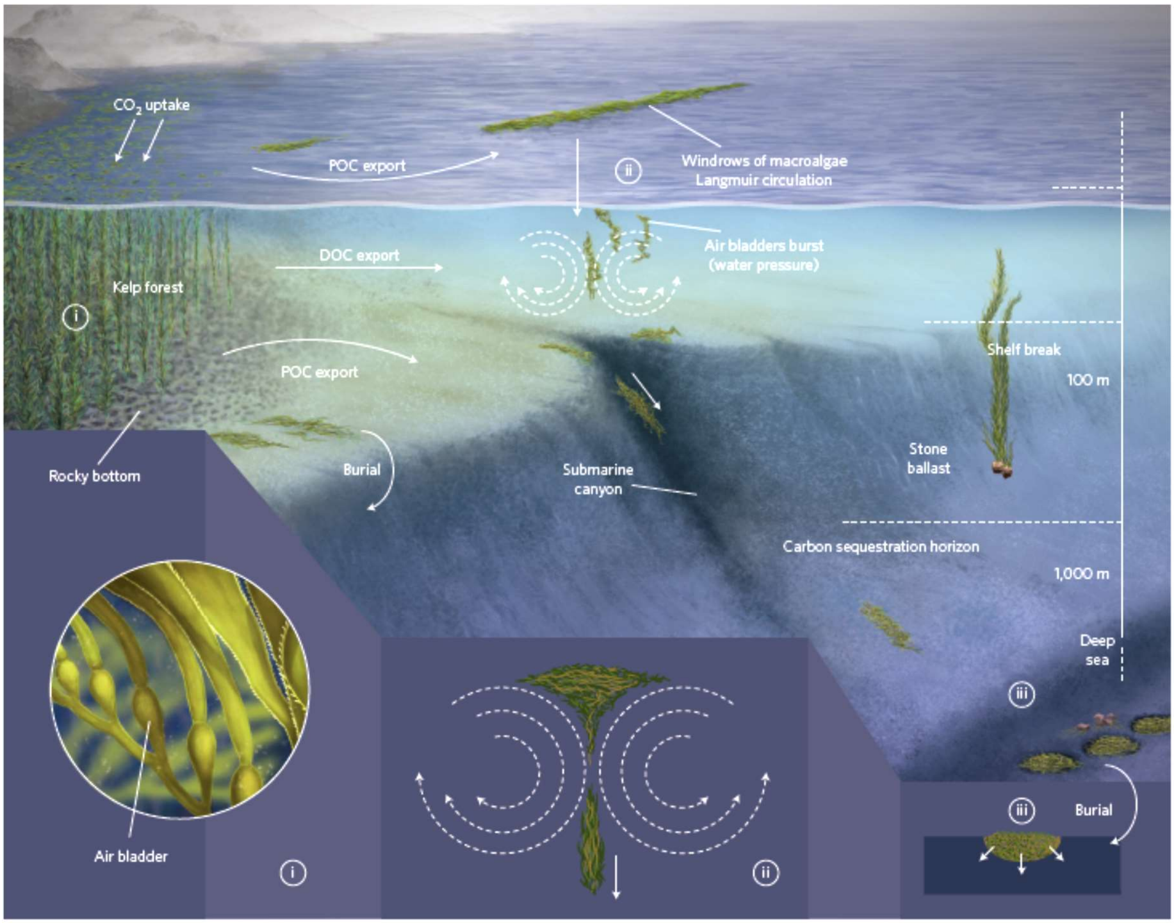

Figure 3. "*Conceptual diagram of the pathways for export and sequestration of macroalgal carbon. Air bladders are common among brown algal taxa and facilitate their long-range transport (i). Langmuir circulation forms windrows of macroalgae (ii) and can force the algae to depths where water pressure makes the air bladders burst and the algae then sink. Macroalgal carbon can be sequestered either via burial in the habitat or by transport to the deep sea where it is sequestered whether buried or not (iii)*". Sourced from (Krause-Jensen & Duarte, 2016).

Macroalgae (which are the dominant primary producers in the coastal zone), therefore have a much more substantial role as a carbon sink than previously thought (Krause-Jensen & Duarte 2016). Kelp specifically is known to act as a significant carbon storage sink in temperate and polar seas, with global modelled estimates of standing crop biomass ranging from 7.5 to 20 Tg C (Reed & Bzezinski 2009). Current estimates for the total contribution of *all* vegetated coastal habitats (including seagrass, macroalgal beds, mangrove forests and salt-marshes) toward organic Blue carbon sequestration (in shallow sediments and through transport to the deep sea), range from 73 Tg C $year^{-1}$ to 866 Tg C $year^{-1}$ (Duarte 2016). Approximately 55% of total contributions to CO2 capture from all Green carbon is from the Blue Carbon component, despite its far smaller global distribution (Nellemann *et al.* 2009).

Just as on the land, the appropriate managing and accounting for 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, such as seen with the UN (REDD) mechanism for terrestrial forests. A number of recent studies have therefore focussed on quantifying the amount of Blue carbon stored in various habitat types (McLeod *et al.* 2011; Pendleton *et al.* 2012; Macreadie *et al.* 2014; Thomas 2014; Duarte 2016). Others have built on these earlier works to attempt to apply monetary values to the climate change mitigation benefits of these systems' stored and annually sequestered Carbon, and try to incorporate this concept into climate market mechanisms (Lau 2013; Luisetti, Jackson & Turner 2013; Ullman, Bilbao-Bastida & Grimsditch 2013; Canu *et al.* 2015; Murdiyarso *et al.* 2015). The final stage is then to see how to manage these valuable systems into the future in order to protect, restore or enhance their Blue carbon storage benefits (Laffoley & Grimsditch 2009; Zarate-Barrera & Maldonado 2015; Macreadie *et al.* 2017).

The report by (Nellemann *et al.* 2009) shown in Figure 4, illustrates the current range of estimates of total value in US dollars per hectare for a number of well-studied coastal ecosystem carbon sinks. Mangrove forest shows the greatest carbon capture value due to their ability to both store carbon in dense standing stocks and sequester large amounts of organic biomass into their surrounding sediments.

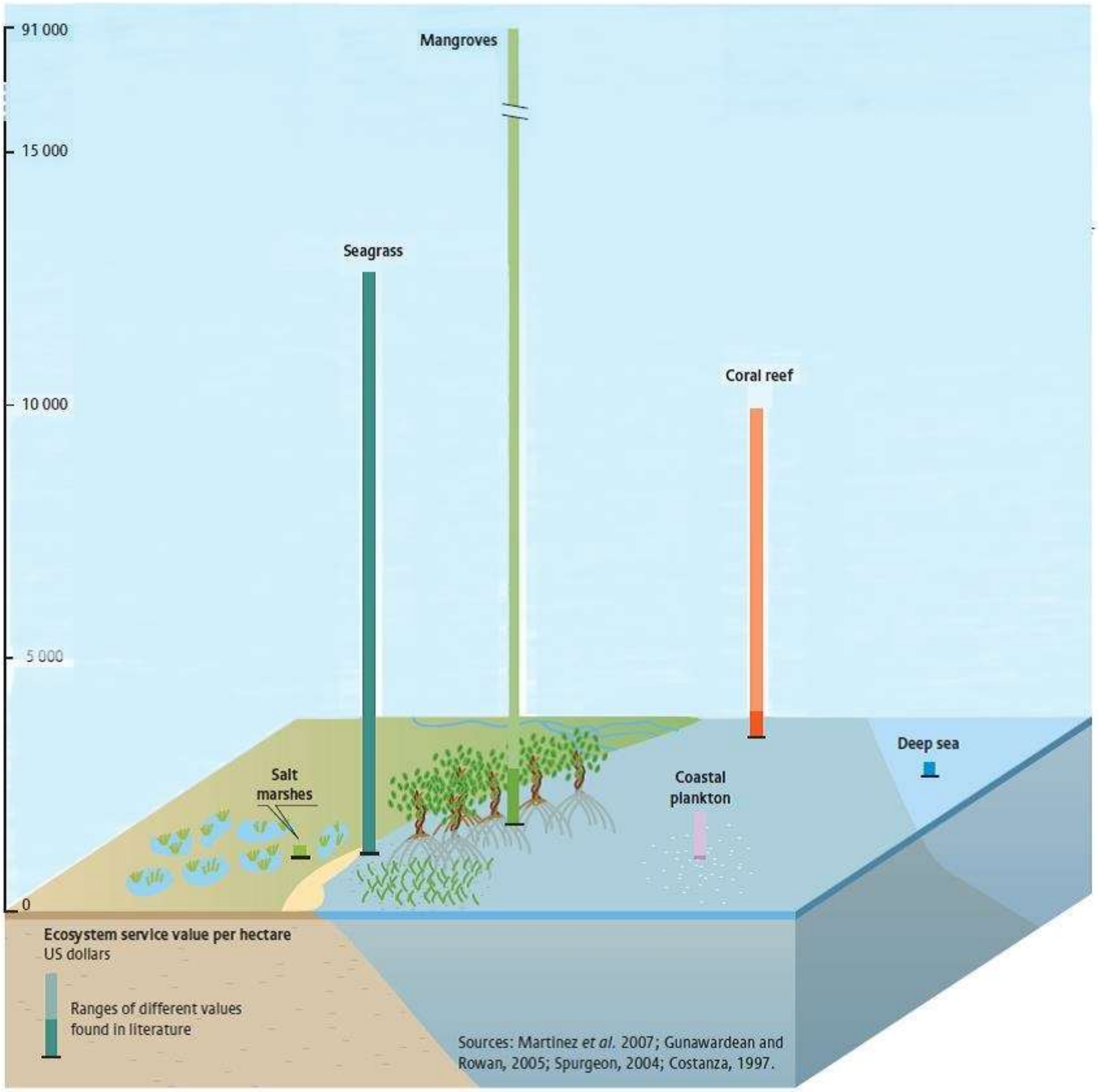

Figure 4. Current range of total valuation estimates of blue carbon sinks per hectare. Adapted from (Nelleman *et al.* 2009).

Social Cost of Carbon

Once an assessment has been made of the quantity of carbon stock and the sequestration rate of an ecosystem, a judgement of the value to assign to that storage must be estimated. The 'Social Cost of Carbon' (SCC) is a term used in climate policy whereby a value is placed on the speculated economic cost or 'marginal cost' of every additional metric tonne of CO_2 equivalent emitted to the atmosphere, including the non-market impacts on health, the environment, well-being etc. In essence the SCC attempts to calculate future damage and mitigation costs of greenhouse gas emissions to humanity globally, and then 'discount' this total value into an appropriate cost in today's money. This estimate once calculated and applied at an individual country level can then be used by government to weigh off policy decisions in terms of climate adaption and mitigation.

To construct the SCC value estimate and project it to the future requires a number of assumptions: First, a range of socio-economic estimates such as population growth are projected; second, a 'climate module' is chosen whereby future environmental and climate responses are predicted (with further assumptions based on which global temperature goal is to be met); third, cost-benefit scenarios are created to evaluate the effects of future climate on both market and non-market variables; and fourth, a 'discount rate' is applied to calculate how much people should pay today to use a resource and mitigate associated damages, versus what people need to pay in the future for the same benefits. The discount rate in particular affects the SCC value, with a higher discount inferring a greater emphasis on easing the financial burden of those alive today (and therefore giving a lower initial SCC value). Or to put it another way, a lower discount rate will give greater weight to costs or benefits occurring in the distant future than to those occurring in the near future, while a higher discount rate will give greater weight to costs and benefits occurring in the near future than in the more distant future. For context, in the report by UK treasury (Stern 2007), a low rate of 1.4 % was recommended, however following a 2009 review this value has shifted to 3.5 % (Harrison 2010; DBEIS 2017).

Using the constructed SCC, individual governments (or groups such as the EU) then typically use market trading within polluting industries (i.e. 'Cap and trade' schemes such as the EU Emissions Trading Scheme), set at regional prices (World Bank, Ecofys & Vivid Economics 2016), and mix this with a range of corresponding carbon / pollution taxes to meet their speculated targets.

Project aim

This study aims to estimate the current extent and density of *Macrocystis* kelp forest found within the Falkland Islands, analyse if this distribution is stable or changing, and then apply a monetary valuation to both the carbon stored and the carbon sequestered annually to deep sea sediments within this system, based on published values of the SCC.

2. Methodology

2.1. Distribution and density

The GIS layer depicting the giant kelp (*Macrocystsis pyrifera*) distribution was obtained from the IMS-GIS data centre (South Atlantic Environment Research Institute). The file, which came from the Marine Spatial Planning database, had been manually digitised throughout the Falklands Islands using Google Earth imagery (based on 2016 DigitalGlobe datasets). Areas visibly covered by surface floating kelp fronds were converted to spatially explicit KML polygons, giving an accuracy of approximately 3 metres (Figure 5). The polygons were then converted to shapefiles and imported to ArcMap™ for analysis of total area using the 'Calculate Geometry' tool.

Figure 5. An example of the spatial digitisation of current kelp extent, using the outline of visible kelp fronds on the surface waters surrounding the Falkland Islands.

Giant kelp density was calculated based on field survey data collected from across the Falkland Islands by the Falklands-based 'Shallow Marine Survey Group' (http://www.smsg-falklands.org/), with a total of 386 surveys conducted between 2008 and 2016 (Figure 6). Density values were based on the number of individual giant kelp holdfasts observed in-situ one metre either side along a 20 m transect placed randomly on the seabed within the kelp forest habitat.

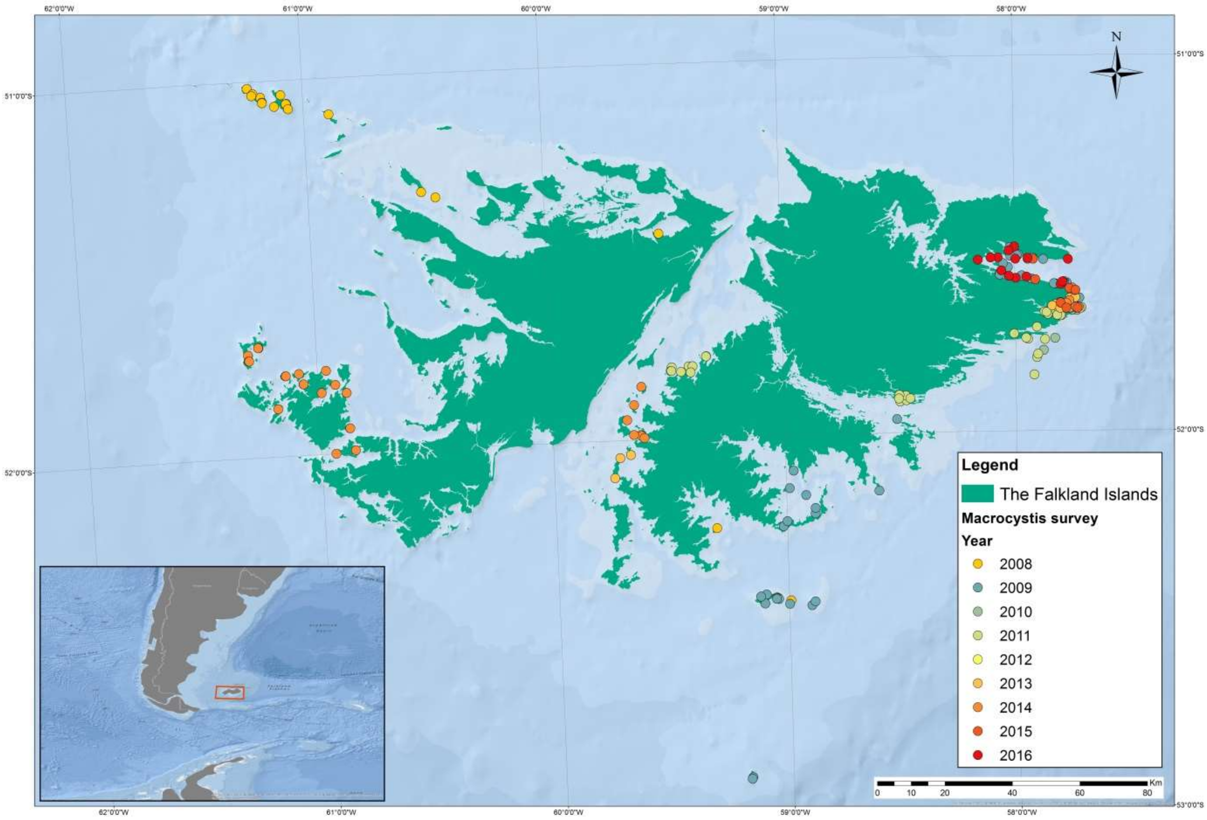

Figure 6. Site locations of annual SMSG benthic surveys of kelp conducted within the Falkland Islands between 2008 and 2016 (WGS/UTM 21S projection).

Density per square metre for each survey was then averaged across the known distribution for Autumn (March – May) and Spring (September – November) surveys to account for any seasonal changes in density as the forest thins. Density calculations were initially further sub-divided to the East and West of the archipelago to account for any differences in abundance caused by the different temperature water currents surrounding the Falklands islands, (with the Eastern Falklands Islands Current being generally colder than the West), although any differences were shown to be negligible.

2.2. Biomass stock

Macrocystis 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, for the season within which the kelp was surveyed by the SMSG. This assessment assumes a broadly consistent average thalli height across the Falklands. Dry weight was estimated as 10 % of wet weight, and the weight of carbon contained per kilogram of biomass was estimated as 30% of the plant dry weight, based on previous studies of *Macrocystis* habitat by Reed & Bzezinski (2009). Finally, the mean weight of carbon m^{-2} was multiplied by the calculated distribution of *Macrocystis* 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).

2.3. Sequestration to the deep sea

The net primary productivity (NPP) of *Macrocystis* forest 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 & Bzezinski 2009). It is estimated that for macro-algae growing within soft sediments approximately 0.4% of annual NPP is buried / sequestered in these shallow surrounding sediments (Krause-Jensen & Duarte 2016), however in the context of the Falkland Islands this will be less likely due to the kelp primarily growing on hard bedrock, this process is therefore excluded from calculations.

Following a global analysis by Krause-Jensen & Duarte (2016): it is estimated that sequestration through burial of Particulate Organic Carbon (POC) in deep waters is ~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. Once these values were calculated they were multiplied across the current known extent of *Macrocystis* forest within the Falkland Islands and converted to CO_2 equivalent (CO_2e) weight.

2.4. Carbon values

Social Cost of Carbon (SCC) values were calculated based on mean values from 211 studies in grey and peer reviewed literature (Tol 2008). Due to the high deviation in estimates and uncertainty of the SCC (with values ranging from many thousand dollars to less than one), Tol (2008) applied three different kernel density estimators, using Fisher-Tippett and Gaussian distributions to the values from all studies to give estimates of mean values. Mean values across the distributions ranged from $88 - 127, and here we apply the middle estimate of $102 USD per tCO_2e, using a Gaussian distribution of all values.

To further give context to this study using more recent valuations, and to give future extrapolation values under different scenarios, we use a study by Nordhaus (2017) and incorporate it with UK Emission Trading Scheme market estimations (DBEIS 2017). Both studies use various scenarios and discount rates to cost the benefit to society of 1 metric ton of CO_2e extracted from the atmosphere and estimate for future SCC in 2030 based on each scenario. These values were then applied to current estimates of carbon content and sequestration 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 to be substantial.

3. Results

3.1. Distribution & density

The distribution of *Macrocystis* kelp forest surrounding the islands of the Falklands was found to cover a current area of approximately 664 km^2, based on data derived from Google Earth satellite imagery (Figure 7). This represents ~ 0.02 % of the estimated mean global area of all macroalgae, set at 3.54 million km^2 (Krause-Jensen & Duarte 2016).

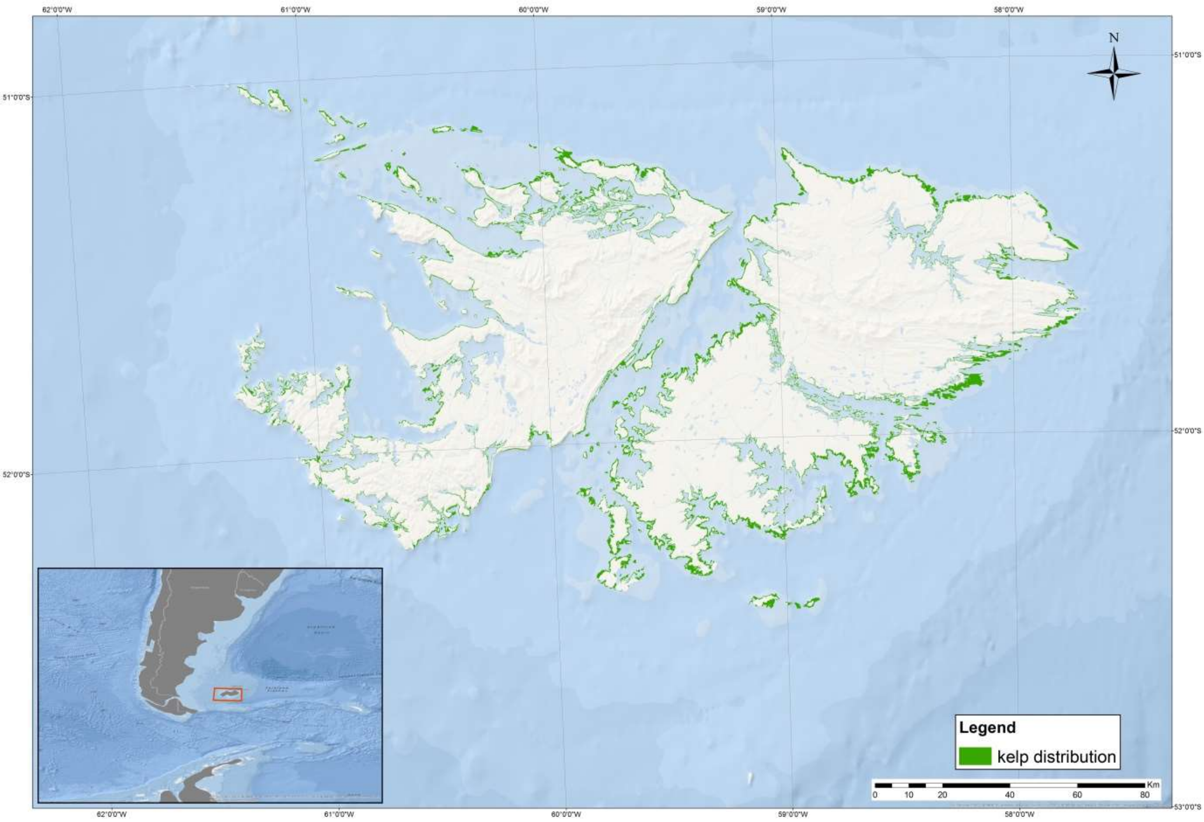

Figure 7. Mapped extent of *Macrocystis* kelp forest surrounding the Falkland Islands, based on 2016 GoogleEarth Imagery.

Measures of mean density were highly variable, ranging between ~0.15 and 0.85 thalli / m^2, with a mean of 0.401 thalli / m^2 (SE = ± 0.034) across all years (Figure 8).

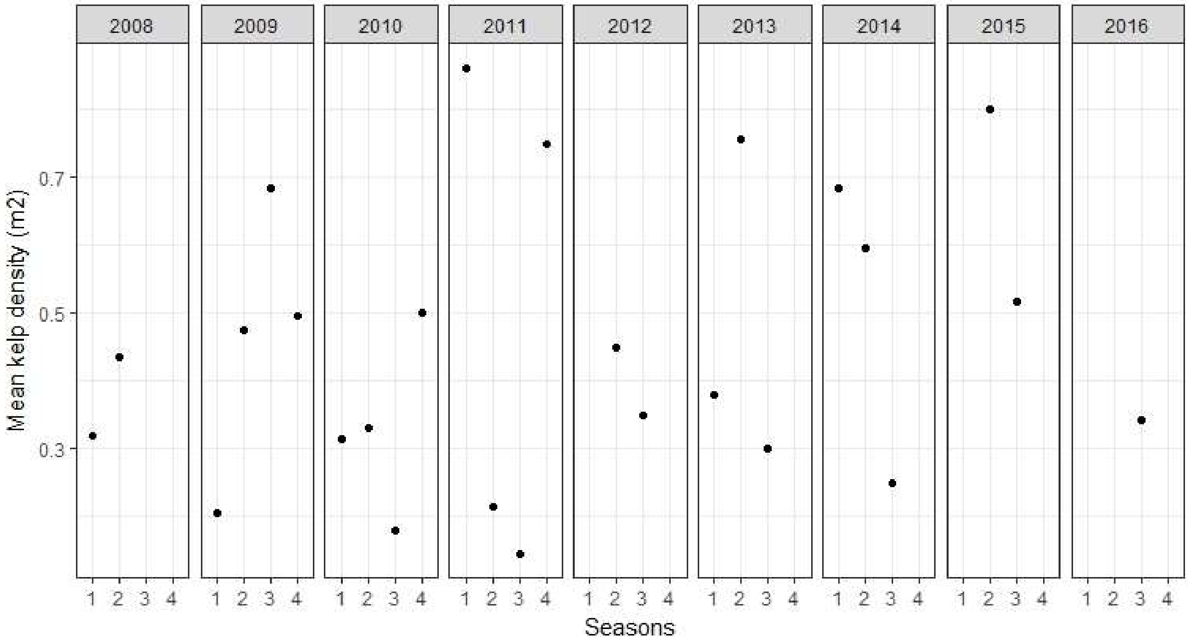

Figure 8. Seasonal values of mean *Macrocystis* forest density (individuals/m^2) from 2008 to 2016, with 1 = Spring, 2 = Summer, 3 = Autumn, 4 = Winter.

There was a slight overall density decline of −0.024 thalli m^2 yr^{-1} across the Falkland Island ecoregion (Spalding *et al.* 2007) from 2008 to 2016, in line with the globally averaged kelp decline of −0.018 yr^{-1} (Krumhansl *et al.* 2016). However, this decline is non-significant ($p>0.1$) due to the large variation seen and an apparent underlying cycle of growth and decline in density of ~ 3-4 years (Figure 9), indicating an overall stable kelp community. The highest survey density was seen in 2009 with 0.530 thalli / m^2, and the lowest seen in 2015 with 0.195 thalli / m^2.

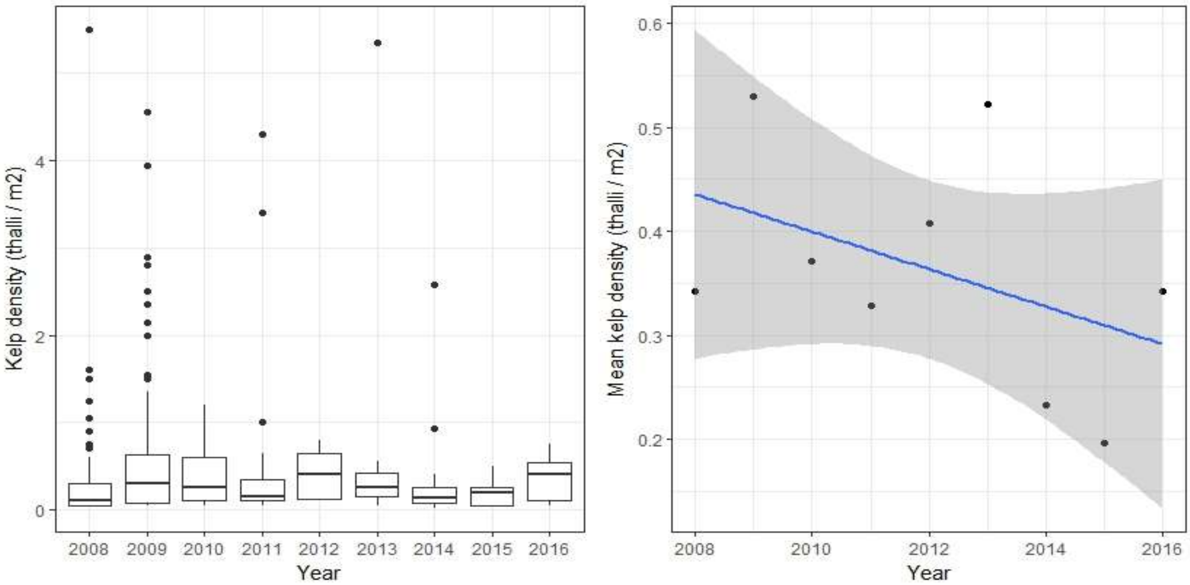

Figure 9. Yearly boxplots of *Macrocystis* forest density (individuals/m^2) from 2008 to 2016, along with yearly averaged linear trend of mean density.

3.2. Biomass

Following measurements of kelp biomass recorded by (Van Tussenbroek 1993), and assuming dry weight to be 10% of wet weight (Reed & Bzezinski 2009), mean thallus weight was found to be 0.74 kg (averaged across all years). Applying the known mean density of kelp and assuming carbon content to be ~30 % of dry weight (Reed & Bzezinski 2009), mean carbon weight was seen to be 0.09 kg m^{-2}. This gives an average overall carbon standing stock of 0.06 Teragrams (million tonnes) within the giant kelp across the Falkland Islands, or 0.3 – 0.8 % of the global stock (Table 1), and is equivalent to ~ 266 million individual kelp across the archipelago.

Table 1. Density and carbon standing stock of kelp forest held within the Falkland Islands. *carbon weight assumed to be 30 % of dry weight, following Reed and Bzezinski (2009).

	Spring	**Autumn**	**Averaged (all seasons)**
Mean thallus Weight (wet) kg / m^2 (Van Tussenbroek 1993)	8.00	1.40	-
Mean thallus Weight (Dry) kg / m^2 (Van Tussenbroek 1993)	0.80	0.14	-
Density thalli / m^2 (Van Tussenbroek 1993)	0.62	0.72	-
Mean thallus dry weight kg (Van Tussenbroek 1993)	1.29	0.19	0.74
Mean density of thalli / m^2 (SMSG, 2008-2016)	0.33	0.53	0.40
Macrocystis carbon content (kg /m^2)*	0.13	0.03	0.09
Falkland Island kelp distribution in 2016 (km^2)	664.05	664.05	664.05
Total mean number of thalli (million)	411.71	478.11	266.28
Total carbon standing stock TgC	0.08	0.02	0.06
Total carbon dioxide equivalent (million tonnes CO_2)	**0.31**	**0.08**	**0.22**
Global % of stock - lower estimate (7.5 TgC)	1.13	0.28	0.79
Global % of stock - higher estimate (20 TgC)	0.42	0.10	0.30

3.3. Sequestration

Figure 10 illustrates the annual flow of carbon from standing kelp forest to re-mineralisation, grazing or sequestration using the averaged value of NPP (985 g C m^{-2} yr^{-1}) for a typical *Macrocystis* bed, following the carbon flows described by (Krause-Jensen & Duarte 2016).

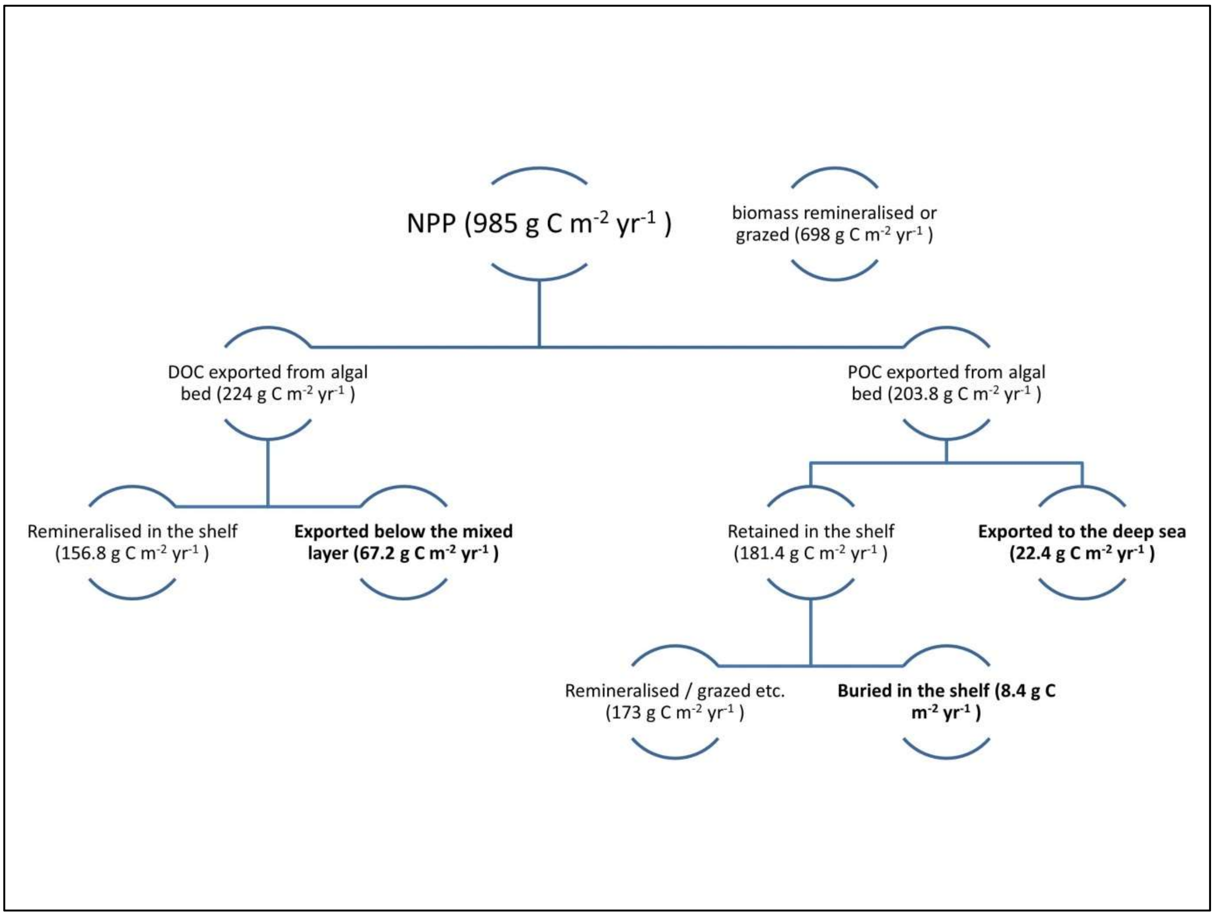

Figure 10. Flow of carbon from a macro-algal bed to sequestration in the form of i) Particulate Organic Carbon (POC) exported to the deep sea, ii) POC buried in the benthic shelf, or iii) Dissolved Organic Carbon (DOC) exported below the water's mixed layer. Net Primary Productivity (NPP) based on (Reed & Bzezinski, 2009) and flow percentages based on average values from (Krause-Jensen & Duarte, 2016). Sequestered Blue Carbon shown in bold.

Applying the average values detailed in Figure 10 to the Falkland Island's current *Macrocystis* forests gives a total average blue carbon sequestration value of 0.065 Tg carbon year^{-1}, or an equivalent of 0.239 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 Macrocystis forests per year based on current known distribution and NPP rates of 670-1300 g C m^{-2} y^{-1}.

Sequestration route		**Year^{-1}**	
	Minimum	**Average**	**Maximum**
POC buried in shelf (Tg)	0.004	0.006	0.007
POC exported to deep sea (Tg)	0.010	0.015	0.020
DOC Exported below the mixed layer (Tg)	0.030	0.045	0.059
Total sequestered Blue carbon (Tg)	0.044	0.065	0.086
Total sequestered CO_2 (million tonnes)	**0.163**	**0.239**	**0.315**

3.4. Valuation

Using the mean value of SCC from Tol (2008) of $102 per tCO_2e (USD), and taking the conservative average measures for both standing stock and annual sequestration, the Falkland Islands have a current standing stock of $22.20 million, with the annual sequestration of carbon to the deep sea valued at $24.38 million yr^{-1} (ranging from $16.58 – 32.17 million). The data suggests that the extent and of kelp and therefore rate of sequestration will remain fairly stable for the foreseeable future, unless any new pressure is placed on the system, either from future habitat destruction, or through tropicalization via climate change.

For further reference and context, Table 3 details model scenarios for the future SCC value in 2030 of the kelp resource in the Falkland Islands based on various starting SCC values and discount rate scenarios in 2015 from Nordhaus (2017) and DBEIS (2017). These estimates give a future 2030 average stock value of $47.81 million (ranging from $11.23 – 81.88 million across SCC estimates), and an annual sequestration value of $52.49 million (ranging from $12.33 – 89.90 million across SCC estimates).

Table 3. Values given in US dollars for the mean calculated Blue carbon (CO_2e) standing stock, and mean annual Blue carbon sequestration to deep sediments for FI kelp forests. Scenarios are shown between the year 2015 and 2030 (using modelled values). Carbon pricing scenarios based on a range of recent literature spanning low and high estimations of SCC: *1 = (DBEIS 2017); *2 = (Nordhaus 2017); *3 = (Stern 2007). For detail on the modelling used see (Nordhaus 2017) on which the estimations are based.

2015 **Scenario**	**Carbon value** **(USD ton^{-1} CO_2e)**	**Standing stock** **(million USD)**	**Sequestered year^{-1}** **(Million USD)**
Trading price UK *1	5.39	1.17	1.29
SCC for 'business as usual' (BAU) emissions scenario *2	31.20	6.79	7.46
SCC for 2.5 degree maximum warming scenario *2	184.40	40.13	44.07
SCC (Stern) *3	197.40	42.96	47.17
Average value	104.59750	22.76559	17.00290
Mean SCC from Tol 2008	**102.00**	**22.20025**	**24.38**

2030 **Scenario**	**Carbon value** **(USD ton^{-1} CO_2e)**	**Standing stock** **(million USD)**	**Sequestered year^{-1}** **(Million USD)**
Trading price UK *1	99.77	21.71	23.84
SCC for 'business as usual' (BAU) emissions scenario *2	51.60	11.23	12.33
SCC for 2.5 degree maximum warming scenario *2	351.00	76.39	83.88
SCC (Stern) *3	376.20	81.88	89.90
Average value	219.64	47.81	52.49

This valuation shows that giant kelp contributes to climate mitigation an average ~ \$0.033 m^{-2} (USD) in terms of standing stock along the coast of the Falkland Islands and a sequestration value of ~ \$0.037 m^{-2} $year^{-1}$ (USD), (while current kelp populations remain stable). Figure 11 shows an interpolated value map for kelp forest value per m^2 for the Falkland Islands across the current known distribution.

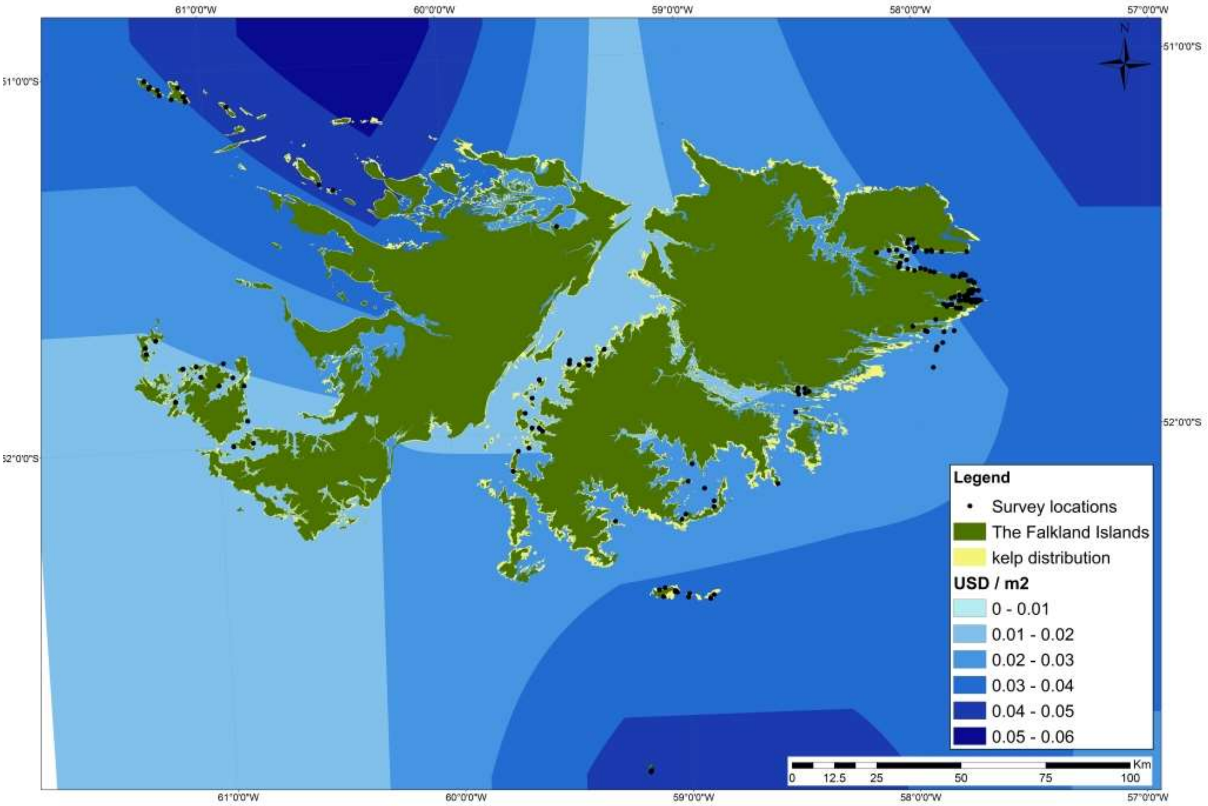

Figure 11. Value per m2 of kelp forest for the Falkland Islands. Value was calculated based on averaged biomass densities at sampled locations multiplied by present day averaged SCC. Points interpolated across the region using Inverse Distance Weighting (shown with blue bandings), and **apply ONLY to the known distribution of kelp (shown in yellow)**.

4. Discussion

This analysis showed that both the carbon standing stock and amount of carbon sequestered each year by the giant Kelp habitat is extremely valuable to humanity both now and in the future, in terms of its ability to regulate climate and mitigate future damage. While in the Falkland Islands the system appears healthy and stable currently a great deal of uncertainty still exists on how this habitat will fare into the future. In the 'state of the environment' and Biodiversity Framework reports produced by Falkland Islands Government (Otley *et al.* 2008; FIG Environmental Planning Department 2016), a number of risk factors exist for kelp, which need to be appropriately managed to avoid any degradation (and subsequent loss of value) of this system. High priority threats are from potential invasive species and biosecurity issues, along with medium and low threats from development (habitat conversion) in coastal regions, pollution, 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 potential damaging effects of tourism. Overarching all of these threats are potential changes associated with future climate. While the majority of these threats are well managed, uncertainty associated with climate impacts is likely to be the highest concern over the coming years. Kelp is to some degree resilient to acute temperature fluctuations (Reed *et al.* 2016), but increases in storm occurrence, chronic temperature changes and shifting of key associated species' range will all still drive changes to this habitat (Krumhansl *et al.* 2016; Pecl & et al 2017). The best way therefore to sustain Blue carbon benefits and limit some of these threats (aside from working towards attaining global emission reduction targets), is through good sustained local management (Macreadie *et al.* 2017).

This study would benefit from a number of additional elements if further monitoring allows. Firstly, it is important to have long terms data on the actual extent of the kelp forest habitat around the Falkland Islands year on year in order to record any changes in distribution (and the rate at which they are occurring). Secondly, 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 and would be in great threat if future deep sea fishing / extraction / damaging activities were to start in these highly sedimented areas. Thirdly, while smaller kelps such as *Lessonia* and *Durvillaea,* which also occur in in the islands in high abundances (and typically in the same distribution range as *Macrocystis*), were not included in this specific analysis, they too will add some additional annual carbon sequestration value to the region and should be included in any management.

Finally, it is worth considering the two further points. First of all Blue carbon storage is just one of a host of ecosystem services that *Macrocystis* kelp forest provide to society, and it is important to not think of each service in complete isolation. Instead it is best to regard all the services as an interlocking system, each providing some value, but providing a greater collective value when all functioning well.

Second, when valuing any carbon regulating service using the 'Social Cost of Carbon' method, it is important to keep in mind that this metric is essentially a construct that we have applied which incorporates a large amount of uncertainty, ethical judgements, political beliefs and regional variation. While this is very useful as a tool for conceptualising value and debating cost-benefits of a service for policy making, it is not in any way an absolute value, and future society may see its worth change dramatically over the years as knowledge increases or perceptions change.

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