The Great Yorkshire Kelp Project

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List of Figures

List of Tables

1 Executive Summary

The term 'kelp' refers to large brown seaweeds of the order Laminariales. Common names for kelp species are: oarweed, tangle, cuvie and sugar kelp. All of the kelps found on the Yorkshire coast grow quickly and form dense stands on lower shore and subtidal habitats if a hard substrate is present. Kelps contribute to the 'blue carbon' pool. Blue carbon stocks are areas of saltmarsh, seagrass, and high-density seaweeds including kelp forests, as well as carbon-rich sediment layers on the continental shelf. Identifying the area and extent of the underwater kelp forests occupying the rocky reef habitats of the Yorkshire coast is the aim of this project. Funding has been given by the local governments of North Yorkshire and the East Riding of Yorkshire, as well as the Environment Agency, to understand the role of kelp, and its significance in the regional carbon cycle.

The research took place from May 2024 to March 2025 and consisted of three phases: firstly, preliminary studies identified areas of the Yorkshire coast that were likely to hold significant areas of kelp forest. Secondly, underwater video surveys and SCUBA diving were used to quantify kelp presence along selected transects in the target zones, and to collect specimens for analysis. Finally, remote sensing images of the Yorkshire coast, obtained from optical satellite photographs, were examined and used as a basis for a predictive model that provides both the number of kelp and total biomass in terms of carbon.

The video surveys covered 1.3 hectares and showed that kelp was present in all the expected areas. The Yorkshire kelp forest consisted of three main species. On the lower shore, at the level of low tide of spring tides, the sugar kelp (*Saccharina latissima*) was found in more sheltered locations such as Flamborough South Landing and Runswick Bay. Tangle (*Laminaria digitata*) was found at a similar shore height in more exposed locations such as Selwicks Bay. Underwater, the zone from the lowest low tide level to a depth of three metres was occupied by a dense coverage of the largest of the three species, forest kelp (*Laminaria hyperborea*). Previous records of *Laminaria hyperborea* from surveys conducted in the 1970s show a lower depth limit of over 7 m below chart datum (BCD). However, the present-day extent is considerably shallower than this, with dense kelp forest mostly not extending beyond 5 m BCD. The cold-water kelp known as dabberlocks (*Alaria esculenta*) was not recorded, even in areas such as Filey Brigg, where it has been observed in the past.

Analysis of the underwater video was conducted to quantify the abundance of kelp. This also revealed rich associated fauna and flora amongst kelp beds. Wrasse (*Labrus spp., Symphodus sp.)* were the most common fish, along with commercially important pollack (*Pollachius pollachius*). Other fish species including cod (*Gadus morhua*) and bass (*Dicentrarchus labrax)* were also recorded. Additionally, commercially important crustaceans including crab (*Cancer pagurus*) and lobster (*Homarus gammarus*) were recorded. Rock surfaces below the kelp zone were often dominated by large numbers of edible sea urchins (*Echinus esculentus*) and species of starfish (e.g. *Asterias rubens*). Grey seals (*Halichoerus grypus*) and bottlenose dolphins (*Tursiops truncatus*) were frequently observed in the near-shore zone during the video and dive surveys.

Surveys were timed to sample the kelp stock during summer, at the end of their growth season. This is a period when old blade growth from the previous season has been shed, but prior to any losses through autumn storm action. It is also the period when the length of the algal blades is greatest. Measurements of photosynthetic activity on kelp samples retrieved by the dive teams indicated that the algal material had a high level of photosynthetic ability and was not impacted by environmental stress (e.g. high irradiance, nutrient deficiency, high temperature).

Data on the proportion of carbon contained within kelp tissues derived from CHN analysis was used in the conversion of kelp biomass to carbon quantities per individual kelp. Kelp tissues were in a healthy state and the carbon content of individuals was very similar to previously published values from other geographic regions within the UK. Satellite remote sensing combined with underwater video was used to estimate the numbers of individual kelp per square metre for the entire Yorkshire coast. Densities varied over small spatial scales, but were greatest near Whitby and Cayton Bay, and lowest under the cliffs of Ravenscar.

By scaling up the values of carbon per individual kelp, in combination with estimates of kelp density, an accurate estimate of total carbon stock was obtained. To account for carbon export to the surrounding environment during the annual growth period, estimates of carbon production were calculated through the conversion of blade biomass to carbon quantities. This was done for two species of kelp, *L. digitata* and *L. hyperborea*, since these species follow the same growth pattern whereby old-growth lamina material is released and shed into the surrounding environment each year. An estimated total carbon stock for the entire Yorkshire coast was produced, totalling 2000 tonnes. This estimate is considerably lower than previous estimates for the area.

A possible reason for the lower estimate may be due to our more accurate measurement of kelp forest depth penetration, which is lower in Yorkshire than many other parts of the UK. Reasons for this lack of kelp forest at depth remains to be understood, but possible factors include light limitation though water turbidity, and grazing pressure from the sea urchin *Echinus esculentus*.

2 Introduction

The UK is moving towards a carbon-neutral economy. This means that the overall emissions of carbon dioxide and other greenhouse gases (GHG) will eventually be greatly reduced relative to today's levels. However, some unavoidable emissions will remain from industries that are difficult to decarbonise. These residual emissions will need to be offset by atmospheric carbon reduction strategies in order to achieve net zero emissions. Proposed methods include direct carbon capture from the air, carbon capture and storage, or the use of vegetation to trap CO_2 via photosynthesis. Carbon accounting requires a stock-take of all sources of GHG to the atmosphere and a recognition of processes that remove said gases. Among the relatively well-characterised 'sinks' for carbon are areas of terrestrial vegetation such as forests, moorland and peat, and wetlands. Equivalent areas in the marine environment are less well studied, hence the current interest in quantifying 'blue carbon' stocks (Smeaton et al., 2023).

Blue carbon stocks are areas of saltmarsh, seagrass, and high-density seaweeds including kelp forests, as well as carbon-rich sediment layers on the continental shelf. Japan was the first country to recognise blue carbon habitats in its national carbon stock-taking exercise (Kuwae et al., 2022), and it is likely that other countries will follow as part of their own nationally declared GHG contributions.

Large seaweeds and kelp occupy shallow rocky reef habitats and are estimated to have a global extent of between 6.1 and 7.2 million km^2 (Duarte et al., 2022). Across this area, Net Primary

Productivity (NPP) from seaweed habitats is estimated to be 1.32 Pg[1] C/year, making macroalgal habitats comparable in both scale and productivity to the Amazon rainforest (Duarte et al., 2022).

In the UK, moves towards blue carbon accounting are in progress in several national projects such as the marine Natural Capital Ecosystem Assessment (mNCEA) programme funded by Defra. Regular updates on this and other projects are given at annual Restoring Meadow, Marsh and Reef (ReMeMare) meetings organized on behalf of the Environment Agency and held in Scarborough. Local authorities are important partners in this process, and funding is in place to help the economy of North Yorkshire and the East Riding of Yorkshire and their respective Councils move towards carbon neutrality. The Yorkshire Marine Nature Partnership, in discussion with government agencies, non-governmental organisations and academics, identified a regional research gap on blue carbon, and kelp forests in particular. This resulted in the Great Yorkshire Kelp Project being funded.

Kelp in this context refers to the large brown seaweeds of the order Laminariales. In Yorkshire, three species are dominant: *Laminaria hyperborea* (tangle or cuvie) is the largest species with upright stipe of up to 2 m supporting a large blade. Around the UK, it is the competitively dominant species from 2 to 15 m below low water. *Laminaria digitata* (oarweed) competes with *L. hyperborea* in the shallow subtidal and has a shorter, more flexible stipe. In more sheltered locations *Saccharina latissima* (sugar kelp) may replace the *Laminaria* species and become dominant on the low shore. A less frequently found Yorkshire kelp is *Alaria esculenta* (dabberlocks), previously recorded only in sites with extreme wave exposure. The primitive kelp *Saccorhiza polyschides* (furbelows) is present in Northumberland but not further south, and the non-native kelp *Undaria pinnatifida* (wakame) is present in Grimsby marina but has not yet been recorded in Yorkshire.

The shoreline of the Yorkshire coast is a suitable kelp habitat. Extensive rock platforms and boulder slopes are found at the base of cliffs and extend for some distance into the subtidal. Canopy-forming kelps require a hard substrate for attachment of the holdfast, as winter storms will tear away any algal thalli that are not firmly in contact with the rock surface. Given suitable conditions of light, wave exposure, temperature, nutrients and hard substrate, kelp forests will form and become the dominant vegetation type. Subtidal kelp forests in the north of Scotland can hold over 20 kg of wet algal biomass m^{-2} (Smale et al., 2016; Smith et al., 2022) equivalent to 1500 g carbon m^{-2} (Smale et al., 2016) with a mean annual production of 340 gC m^{-2} (Smale et al., 2022) [2].

The food and protection offered by kelp forests supports a very diverse community of animals and seaweeds (Teagle et al., 2017; Smale et al., 2022; Jackson-Bue et al., 2023), consisting typically of epiphytes (e.g. the red seaweed dulse), grazers (limpets and sea urchins), and predators (lobsters, cod and pollack). Much of the biomass produced by kelp forests consists of the blade, which is typically lost on an annual basis. Episodic storm events such as Arwen in November 2021 cause very large accumulations of kelp blades, whole kelp thalli, and other seaweeds to be 'washed up' on the strandline. Even larger accumulations of dislodged kelp are likely to be transported out to sea, along seabed current pathways. The fate of kelp detritus is largely unknown but is thought to accumulate in deeper coastal areas (Filbee-Dexter et al., 2018) and deep-sea sediments (Krause-Jensen & Duarte, 2016). Once trapped in deeper sediment layers, kelp fragments will degrade very slowly and hence have a potential for carbon storage on the years-decades scale.

[1] Pg = petagram. 10^{15} g, or 1 billion tonnes.
[2] Carbon per unit area of kelp forest varies greatly for sites around the UK (Smale at al. 2016)

Kelp forests also release significant amounts of dissolved organic carbon (DOC) into surrounding waters, much of which is highly bioavailable and rapidly consumed by microbial communities, forming the base of important coastal food webs (Gao et al., 2021). Some of this DOC may persist longer in the water column, contributing to carbon export and sequestration in deeper marine environments (Ortega et al., 2019). These pathways highlight the important role kelp forests play in coastal carbon cycling and their potential contribution to long-term carbon storage.

2.1 The Great Yorkshire Kelp forest project

The production of a comprehensive map of kelp presence, densities, condition and carbon stocks is the aim of this project. Earlier kelp studies on the Yorkshire coast took place in the 1960s-1970s in response to the threat of industrial pollution. Based in the former Marine Biology Laboratory at Robin Hood's Bay, SCUBA diving surveys recorded the size, density and maximum depth of *Laminaria hyperborea* at selected sites along the north-east coast (Table 1; from Sheppard et al. (1980)). It was noted that there was a 'very reduced penetration of kelps' due to decreased water clarity. This may be an indication of a widespread 'coastal darkening' phenomenon reducing light penetration in the North Sea and Baltic Sea over the past century (Capuzzo et al., 2015). It was considered likely, at the onset of the Great Yorkshire Kelp Project, that the maximum depth of the Yorkshire kelp forest was likely to be similar to that recorded further north at the Farne Islands (10 to 12 m below low water; P. Moore pers. comm; Catherall et al. *In prep*), in contrast to the west coast of Scotland or Ireland where kelp canopies extend to 20-25 m (Smith et al., 2022). Determining the present-day lower depth limit of the Yorkshire kelp forest is one of the aims of this project, as it will enable an accurate estimate of kelp area to be made.

Table 1 Maximum depth below low water recorded for L. hyperborea [from Sheppard et al. 1980]

Location	Maximum depth (m)
Yorkshire	
Whitby	9.5
Robin Hood's Bay	6.5
Scarborough	6.8
Flamborough	9.5
Durham and Northumberland	
Newbiggin	2.5
Marsden	2
Souter	3

More recently, Burrows et al. (2021) estimated a total primary production by kelp in the English waters of the North Sea to be 126,100 tonnes C per year with a total kelp bed area estimated at 379 km^2. Within this area, an estimated 58,400 tonnes of carbon is stored within kelp biomass (Burrows et al., 2021). About 10% of the total production was assumed to be exported to the blue carbon pool. However, these estimates were based on modelling and were not always supported by *in situ* studies. One figure in the report showing kelp extent for the Yorkshire region is inconsistent with what is known. Area A of Figure 1 shows the predicted presence of *Saccharina latissima* on both banks of the Humber estuary, whereas in reality, the Humber is too turbid for any significant seaweed growth. The soft-sediment beaches of the Holderness coast (Area B) were marked in the report as potentially supporting *Laminaria* species, whereas the substratum would be mobile sediments and therefore unsuitable for kelp attachment. Additionally, there are to our knowledge no kelps found south of Flamborough Head. Similar findings on the predicted distribution of *Laminaria hyperborea* were reported in (Johnson et al., 2024), with presence once again being indicated along the soft sediment shores of the Holderness coast. This report also suggests areas of potential for the restoration of *Saccharina latissima.* Multiple locations within the Humber estuary were identified as candidate areas for restoration, however much of this area is habitat classified as intertidal mudflat or seagrass habitat, which are not suitable for the attachment and survival of macroalgal species.

A recent large-scale study of UK kelp productivity included sites in south-west England, Wales and Scotland, but not the east coast of England (Smale et al., 2020a). Hence, there is a requirement for detailed fine-scale mapping of kelp status and distribution in Yorkshire's coastal waters both for regional carbon budgeting, and to guide restoration.

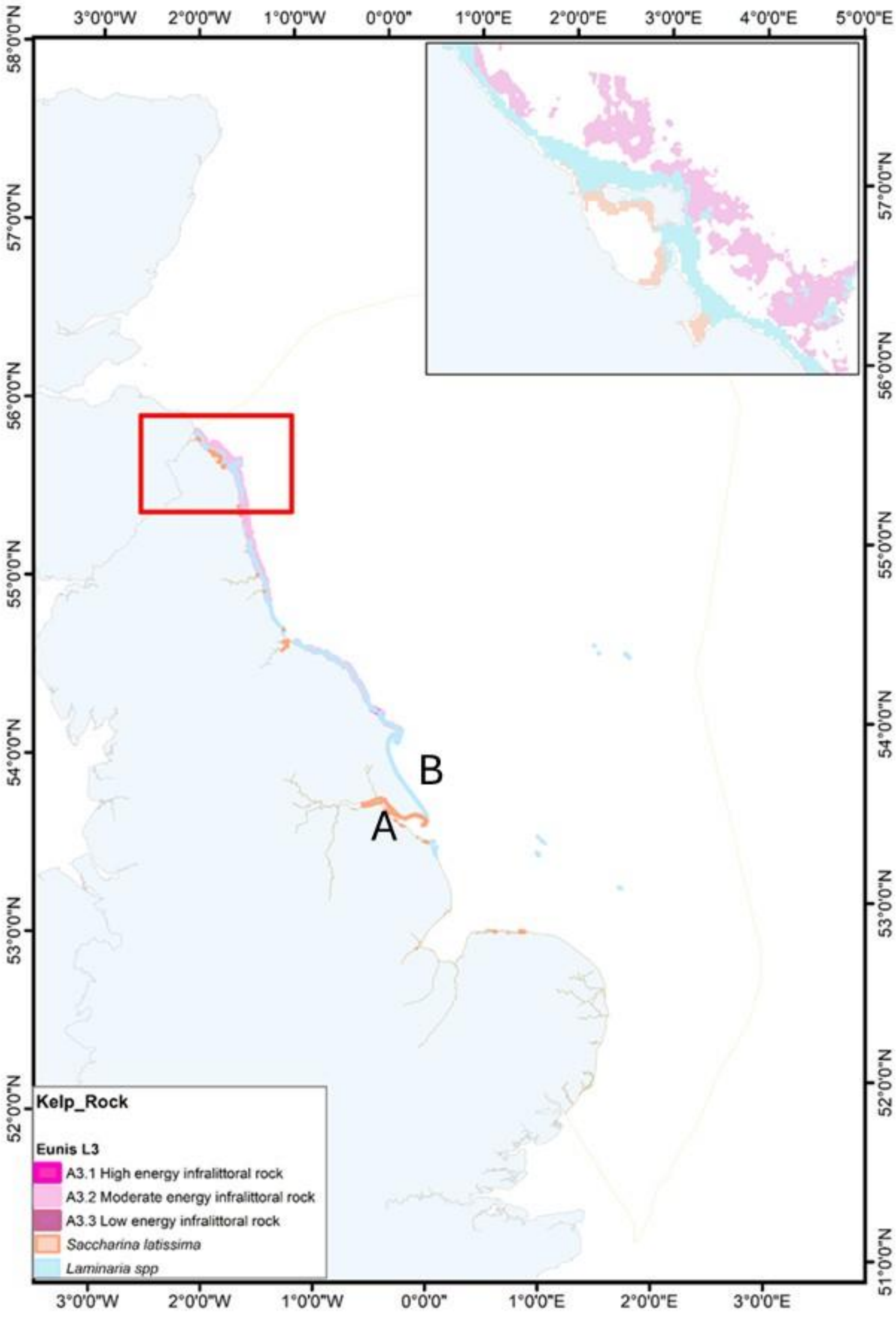


Figure 1 Predicted distribution of kelp blue carbon habitats in England, from Burrows et al. (2021)

3 Methods

The investigations have taken place in three phases: firstly, desk-based studies of the environmental constraints to kelp forest occurrence were conducted in order to identify target areas for detailed underwater search during the summer of 2024. Existing knowledge of recorded kelp locations from UK marine biodiversity atlases was used in this phase

(Figure 2). Target areas covering the north, mid and southern sections of the Yorkshire coast were identified and agreed with the project's external oversight committee (Figure 3).

The second phase of the project was a series of underwater video and SCUBA diving surveys at target sites, including the collection of representative kelp material for detailed analysis in the laboratory.

The final part of the project is the bringing together of the various data layers together with satellite imaging of the seafloor to produce estimates of the standing stock of carbon within kelp. Further details of site selection and other methods are given below.

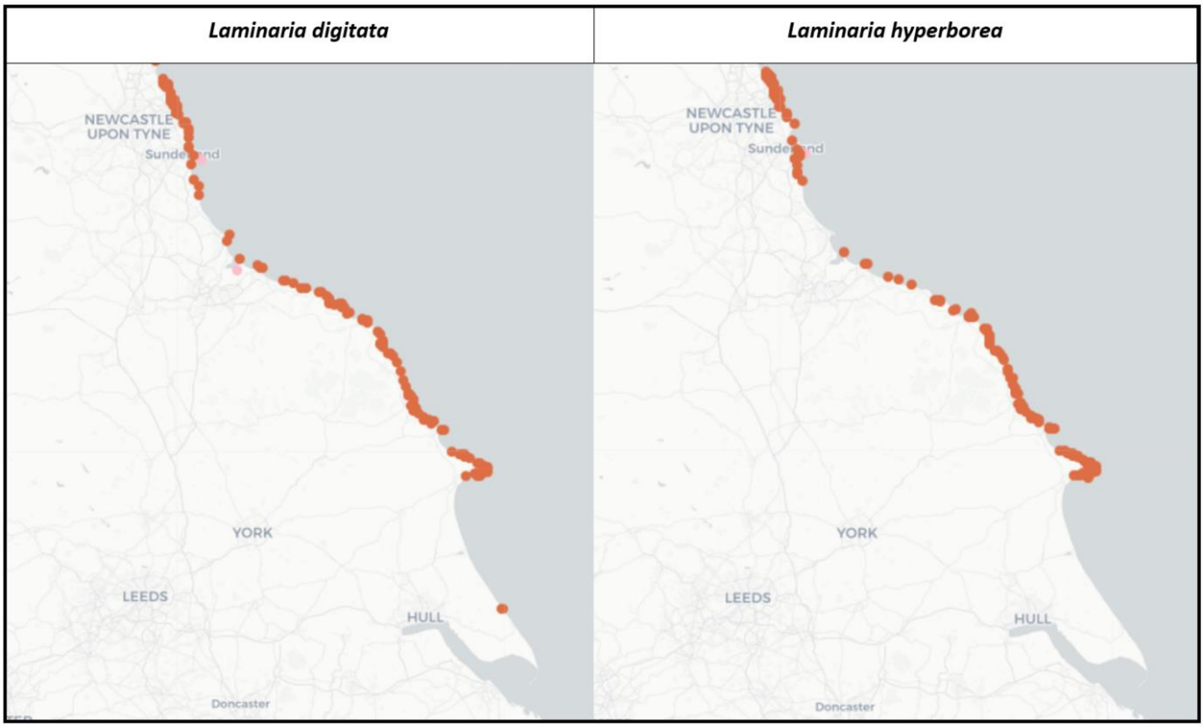


Figure 2 Existing National Biodiversity Network (NBN) records of kelp species (Laminaria hyperborea and Laminaria digitata) presence on the Yorkshire coastline

3.1 Site selection and marine environmental information

Areas of potential high-density kelp forest were selected based on existing knowledge (Figure 2) and with reference to the presence of extensive rock or boulder seabed with depths of less than 15 m. Sites were distributed along the Yorkshire coast to give a representative selection of seabed type along an oceanographic gradient of seawater temperature and water clarity.

For the North Yorkshire coast from Staithes to Robin Hood's Bay, the location selected was Runswick Bay. Here, the rationale was that both sides of the Bay had kelp recorded by previous surveys, with the Marine Conservation Zone designation of the site increasing its importance. The middle section of the coastline from Robin Hood's Bay to Filey Brigg was represented by surveys centred on Cayton Bay and the rock ledges from Cayton to Filey. The southern section of the coast was surveyed primarily on Flamborough Head and Selwicks

Bay in particular, but also included potential kelp areas to the south of Flamborough and including the No-Take Zone at Danes Dyke as well as the main Marine Protected Area (Figure 3). Additional transect surveys were opportunistically made between the main target sites, as described in later sections.

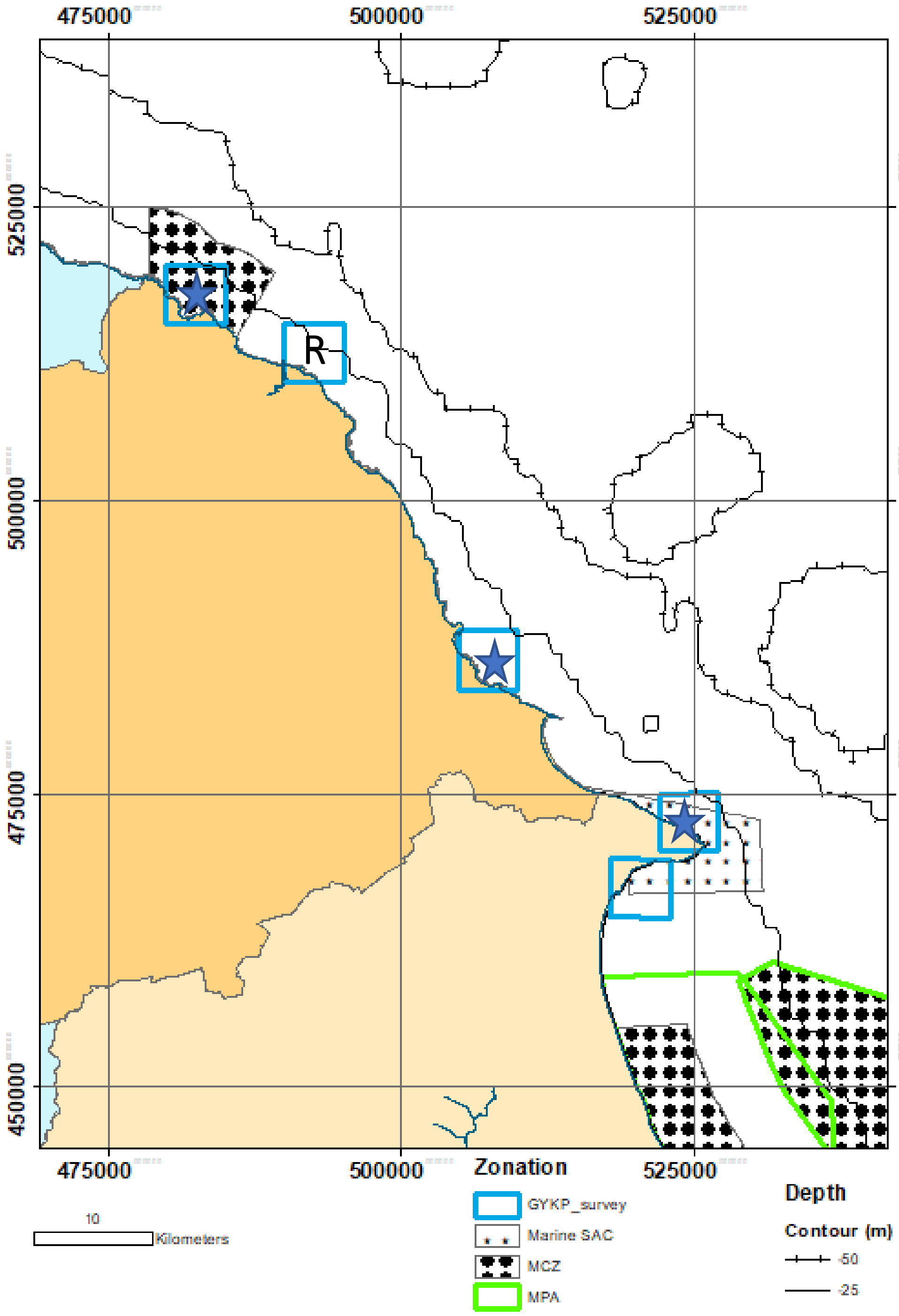


Figure 3 Locations of the target survey areas shown with blue boxes, with a blue star marking the primary survey sites and R indicating secondary sites.

3.2 Oceanography and environmental conditions for kelp growth

Marine environmental conditions for the inshore waters of the Yorkshire coast were extracted from two main marine and coastal data repositories, supplemented by additional oceanographic data collection in association with kelp surveys in August 2024. Hydrodynamic model and remote sensing data were downloaded from the Copernicus Marine Environmental Service at *https://data.marine.copernicus.eu/products* . Water quality data was obtained for stations with a monthly seawater sampling frequency from the Environment Agency water quality portal at *https://environment.data.gov.uk/water-quality/*.

3.3 Survey methods

The presence of the three main kelp species was quantified using intertidal surveys on shores accessible by foot. Offshore surveys from a Rigid Inflatable Boat (RIB) were launched from either Flamborough South Landing, Scarborough or Whitby.

3.3.1 Intertidal

On all shores visited, a shore walkover was conducted and images were taken to determine the extent of the kelp beds. All surveys were conducted at the lowest possible spring tides to determine the abundance of each species of kelp on all the shores with safe access (See Table 1 for details of shore sampling and sample collection). Samples were collected from Holbeck, Scarborough for community analysis to ensure two sandstone shores had been sampled so that the effect of bedrock on intertidal kelp community structure could be examined.

Table 1 Details of the shores surveyed for estimates of intertidal kelp densities, description of kelp communities and where samples were taken for both morphometric analysis and tissue removed from plants to determine photosynthetic efficiency.

Shore	GPS start of survey	Date of samples	Estimates of kelp density	Description of community	Samples for morphology / photosynthetic efficiency
South Landing	54 06 09.7N 00 06 38.0W	19/7/2024	Yes	Yes	Yes
Selwicks Bay	54 07 05.2N 00 04.50.1W	23/7/2024	Yes	Yes	Yes
Filey Brigg	54 12 58.9N 00 15 46.3W	22/7/2024	Yes	Yes	Yes
Holbeck, Scarborough	54 16 06.1N 00 23 13.4W	25/7/2024	No	Yes	No
Boggle Hole	54 25 24.8 N 00 31 29.0W	7/8/2024	Yes	Yes	Yes

Runswick Bay	54 32 13.8N 00 44 39.9W	19/9/20 24	Yes	Yes	Yes

On each platform, at low water, a 25 m transect was placed at random perpendicular to the water's edge across the rock and a 1 m x 1 m quadrat placed at 2 m intervals along the transect, resulting in a minimum of 10 quadrats at each station on each shore. A GPS record of the start and end of each transect was made across the kelp bed. Within each quadrat, firstly the number of individuals of each species of kelp was made by counting the number of holdfasts of each species within the quadrat. Notes were also made of the presence of sporelings, reflecting the recent recruitment of new individuals to the population, although the two *Laminaria* species could not be separated when young. In addition, the number of stipes/holdfasts were also counted within the quadrats reflecting the recent loss on lamina. This provided an estimate of plant density irrespective of % cover. Estimates of mean (SD) densities of each species at each site are presented. Counts were also made of the number of grazing species within each quadrat that were present on the plants and bedrock. Once the quadrats had been completed, 5 individual samples of each kelp species present on the bedrock were detached from the bedrock and placed in individual large bags for return to the laboratory for morphological measurements. The samples were placed in a cool box for transport and morphological measurements and weights made on return to the laboratory. Additional small squares (approximately 3 cm x 3 cm) of undamaged lamina from plants left in situ on the shore were collected across 5 individuals of each species and placed in labelled pots containing seawater. These samples were placed in the cool box on the shore and measurements of photosynthetic efficiency made as soon as the samples were returned to the lab.

In addition, the % cover of all encrusting species (both plants and animals) were recorded in each of 10 individual 1m^2 quadrats in order to describe the overall kelp community present on each shore.

The % cover data collected in the field was imported into PRIMER (Plymouth Routines in Multivariate Ecology) and the data set was square root transformed to downweigh the effect of dominant species in the data. This data was then used to generate a Bray Curtus similarity matrix which produced a number between 0-100 representing how similar each kelp quadrat was to all others within the data set. The matrix was then used to produce an MDS plot which is a non-parametric ordination plot and visually represents how similar each sample is to all others. The Bray Curtis matrix was also used to test the null hypothesis that all there was no significant differences in community similarity between the kelp communities across the shores. This test is a non-parametric equivalent of an ANOVA using the similarity data and produces an overall test to determine if the shores have different communities, then does pairwise comparisons between shores to determine where the overall significance lies between the samples (see Clarke & Gorley. "PRIMER: Getting started with v6" (2005), for full explanation). In addition, the SIMPER routine in PRIMER was used to determine which species were important in defining the similarity of the communities within a shore, and which were important in creating dissimilarity between the different shores.

3.3.2 Subtidal

3.3.2.1 Underwater video capture

Kelp forest presence and abundance were surveyed remotely by drop-down video. Forward (~45°) and downward-looking underwater video cameras (GoPro 5 and 10; Chasing M2) were attached to either a weighted line or a weighted pole on a line, with pairs of equipment deployed on opposite sides of the RIB. Cameras were positioned at approximately 1.5 m above the seabed and kept at a constant height by either visually watching the live video feed (Chasing M2), or by raising and lowering the equipment to touch the bottom at 30 second intervals. The RIB was set to drift passively with its direction determined by the wind and currents, with most drifts starting inshore in shallow water (~0 m BCD) and gradually progressing offshore to depths of ~-8m BCD. Drifts were terminated when no further kelp was visible on the live feed for a period of 5 minutes. The on-screen display of the vessels single-beam sonar was also useful for determining the end-point of kelp forest drifts, as kelp canopy could be seen as backscatter 'clutter' above the seabed. Video surveys took place on eight days of fieldwork in mostly fine weather conditions with sea states between 1 and 4 Beaufort, over the period May 2024 to July 2024 (Table 2). The arrival of dense fog shortened the survey of Flamborough Head on 17/6/24. Between 2 and 12 drifts were achieved per day, with a mean drift length of 10 minutes.

Table 2 List of video survey dates during the spring and summer of 2024. Main target locations are marked in bold.

Target	Launch Sites	Date	Minutes of video quantified
Flamborough	South Landing	19/05/2024	58
Flamborough	South Landing	17/06/2024	34
Flamborough	South Landing	18/06/2024	72
Cayton/Filey	Scarborough	15/07/2024	75
Scarborough to Robin Hood's Bay	Scarborough	16/07/2024	29
Whitby to Robin Hood's Bay	Whitby	17/07/2024	35
Runswick	Whitby	18/07/2024	126
Cayton/Filey	Scarborough	19/07/2024	209

In total, 400 Gb of underwater video were captured over the eight survey days. 637 minutes of video have been scored and quality-controlled at the time of writing. The average drift speed was 10 m per 1 min interval, and the mean field of view (video strip width) was 2 m, hence approximately 1.3 ha of seabed have been covered. This area approximates to 0.01% of the Yorkshire subtidal coastal area to a distance of 500 m from the shoreline (9600 ha).

3.3.2.2 Underwater video scoring

Underwater videos were scored manually by dividing the footage into 10-second segments and calculating abundance and biodiversity parameters for each segment (Table 3). The corresponding JNCC and EUNIS habitat types were also estimated (Parry, 2019). A number of videos were viewed by a second person to ensure consistency between recorders and act as a quality control. Segments in which the seabed was not visible, or in which the camera view was obscured by trailing kelp fronds, were marked as invalid. The actual numbers of various algae and animals were counted directly, or the SACFOR scale of relative abundance was used to estimate algal abundance in the 10 s video clip. Kelp density along the video transect was quantified by counting the number of canopy-forming individuals, sub-canopy individuals and juveniles of less than 30 cm in length, with less developed stipes (following practice of Earp et al., 2024) where feasible. Determination to kelp species level was not always possible from video footage, particularly for juveniles, therefore the abundance of these was recorded according to the SACFOR scale (Strong & Johnson, 2020). In addition, where no kelp appeared during the footage, this was designated as N (not present) for kelp abundance to ensure a clear record of absence rather than a nil result due to camera problems or lack of visibility.

All kelp counts made were also assigned a value according to the SACFOR scale, allowing SACFOR density estimates over a very dense beds or those from a fast-moving video to be included alongside those that were actually counted wherever possible. SACFOR counts were transformed into absolute values using a look-up table.

Table 3 Count categories for each ten-second video segment.

Category	
Individual Mature kelp > 30cm	Total kelp, Total stipe + holdfast, Total holdfast, *Laminaria hyperborea*, *Laminaria hyperborea* with old and new blade, *Laminaria hyperborea* with epiphytes on stipe, *Laminaria digitata Saccharina latissima, Alaria esculenta*
Other brown sublittoral seaweed	*Himanthalia elongata, Dictyota dichotoma, Fucus serratus, Desmarestia sp., Halidrys siliquosa*
Sublittoral red seaweeds	Foliose reds, encrusting reds, filamentous reds, *Delesseria, Phycodrys, Palmaria, Plocamium, Phyllophora, Corallina officinalis, Cryptopleura, Osmundea turf, Calloblephis, Furcellaria, Chondrus/Mastocarpus, Dilsea,*
Sublittoral green seaweeds	*Ulva* sp., *Cladophora* sp.
Animals	Sponges, turf. Barnacles, keel worms, limpets, dogwhelks, *Littorina,* anemones (*Urticina sp,),* Dead mans

	fingers *Alcyonium* digitatum, urchins (*Echinus esculentus*), lobster (*Homarus gammarus*), velvet swimming crab (*Necora puber*), brown crab (*Cancer pagurus*), spider crab, common starfish (*Asterias rubens*), Bloody henry, fish,
Substrate	Mud/silt, sand, gravel, pebbles, cobbles, boulders, bedrock, detritus - organic material, worm casts, unidentifiable
Human impact	Lobster pots, wreckage, litter, line

Example stills from the video footage are provided in Figure 4. This illustrates an excellent image of the benthos viewed through the kelp bed, a shot of a medium density bed when viewed in clear water from above, and an example of a marked change in community structure where an urchin barren is created in an area with high edible urchin abundance (Figure 4).

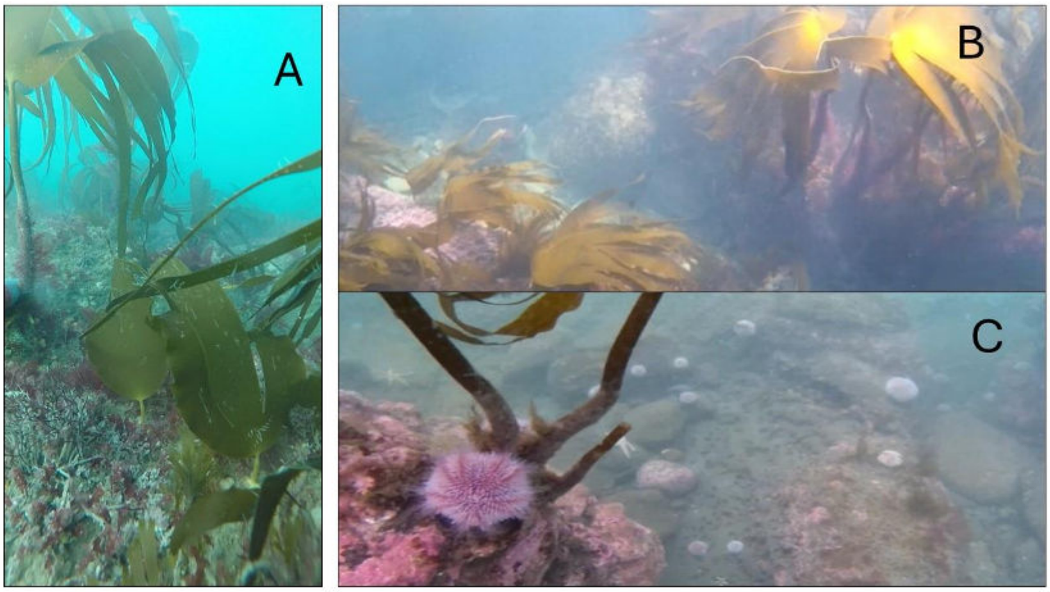


Figure 4 Stills from video footage. A) shows the view of the community when the camera passes through a bed, B) the view of the community from above and C) example of an urchin barren and an edible urchin grazing on kelp.

Pivot tables were used to aggregate the 10-second video counts into one-minute blocks, and a British National Grid geo-reference for each block was assigned from GPS and chart plotter tracks recorded on the RIB. A depth relative to NAP was also assigned to each 1 min block by extracting the value from the most appropriate bathymetric raster file for each location.

3.3.2.3 Sample collection with SCUBA diving

Collections of subtidal kelp samples were conducted at sites at Cayton Bay and Flamborough Head in August 2024. At depths determined from vessel sounder readouts and previous drop-down camera survey, between 5 and 10 canopy forming *L. hyperborea* and occasional *L. digitata* were collected at random for length and biomass estimations by prising the entire holdfast from the substrate and placing the thallus in a black sack (following Earp et al., 2024). Where divers first encountered areas beyond the deepest kelp limit, divers swam inshore until reaching kelp habitat, this location and depth being recorded for specimen metadata and to aid in survey ground truthing.

All dive operations followed the Diving at Work Regulations 1997 (Approved Code of Practice and guidance for Scientific and archaeological diving projects), University of Hull Diving Policy and collection of specimens within project Crown Estate licences.

3.4 Processing of samples

3.4.1 Immediate processing

Kelp samples from shoreline collection and dive surveys were processed identically. Sacks containing the kelp were kept in cool storage and individuals were removed one thallus at a time for identification and processing.

3.4.2 Photosynthetic efficiency using chlorophyll fluorescence

The active chlorophyll fluorescence technique was used to measure key photophysiological variables of kelp sub-samples. Several estimates can be made of an algal species physiological 'health' using non-invasive measurements of changes in the amount of fluorescence emitted. To do this under controlled conditions, a MINI-PAM fluorimeter was placed in a constant temperature room at 14°C and 3 cm^2 sections of blade from the meristem area were brought to the instrument's leaf clip (add photo). The sample was dark-acclimated for 5 minutes, then the maximum photosynthetic efficiency of photosystem-II, F_v/F_m, was measured using a saturating pulse of red light. F_v/F_m measures the potential for light to be converted into stored energy and a large number of scientific references are available for comparative values. A theoretical upper limit to energy conversion in photosystem II is said to be 83% for higher plants, (F_v/F_m of 0.83). In general, F_v/F_m values are lower in brown algae and the theoretical maximum is rarely achieved. An F_v/F_m of above 0.7 indicates a 'healthy' sample; lower values may indicate stress or damage due to temperature, exposure to high light, lack of essential nutrients or disease (Franklin & Forster, 1997; Kromkamp & Forster, 2003).

A further test of kelp physiological status was done by exposing the sample to a series of increasing irradiances, up to the approximate brightness of summer sunlight. This was done as a standard test over a short period of 6 minutes and the values of Electron Transport Rate (ETR) obtained are related to the kelp's ability to grow under different irradiance levels. In general, shade-acclimated deep-water algae have a low ability to use high irradiances but may be more effective at very low irradiances. 'Sun'-acclimated algae may show the opposite. The values of light saturated electron transport (ETR_{max}) and the light saturation point of photosynthesis (E_k) were calculated by curve-fitting through plots of ETR versus irradiance. Sets of five ETR curves from different individual kelps were collected from each depth interval on each sampling day.

3.4.3 Morphometrics

Before any further analysis was undertaken, each plant was laid out on a flat surface and the total length (TL) was measured from the base of the holdfast to the top of the longest blade (Figure 5**Error! Reference source not found.**a). All measurements are detailed in Table 4. The length of the stipe from top of holdfast to start of lamina (SL), the length of lamina from top of stipe to the top of the longest blade (LL) and then the holdfast was measured to determine length (HL), width (HW) and height (HH) from bottom to base to base of stipe.

Figure 5 A) Laminaria digitata laid out for general morphological measurement with tape alongside the plant and B) thin cross-section of Laminaria hyperborea stipe showing the pattern of growth rings evident.

Table 4 The list of morphological measurements made on each kelp plant accompanied by their abbreviations.

Variable and units	Abbreviation when used in text
Total length of plant	TL
Stipe length (cm)	SL
Total Lamina length (longest blade) (cm)	LL
Holdfast length l(cm)	HL
Holdfast width (cm)	HW
Holdfast height (cm)	HH
Stipe diameter at base of stipe near holdfast - two measurements at right angles to each other to account for flattening of stipe (mm)	SDB1 and SBD2

Stipe diameter at top of stipe near holdfast - two measurements at right angles to each other to account for flattening of stipe (mm)	SDT1 and SDT2
Stipe diameter in middle of stipe (mm)	SDM
Blade width at widest point above lamina meristem (cm)	BW
Number of bladelets on lamina	NB
Lamina thickness at base on meristem area- taken using calipers (mm)	LT
No. of rings to age plant (Kain 1963) (*Laminaria hyperborea*)	NR
Weight of holdfast (damp weight) (g)	HWT
Weight of stipe (damp weight) (g)	SWT
Weight of epiphytes on stipe (damp weight) (g)	EWT
Weight of lamina (damp weight) (g)	LWT

We also recorded the dominant encrusting organisms found on the stipe and lamina as a SACFOR estimate of the area and counted the number of mobile organisms, especially grazers, found. The stipe diameter was measured twice at both the base (SDB1 and SBD2) and the top (SDT1 and SDT2) of the stipe with the measurements taken at right angles to account for the flattening of the stipe in some taxa. Only one measurement of the width was taken from the mid-point of the stipe (SDM). Maximum lamina width was taken at the base (BW) and the number of bladelets on the lamina counted (NB). The thickness of the lamina was measured using vernier callipers in the meristem area (LT). The plant was then cut into sections and the weight of the lamina (LWT), weight of the stipe (SWT) and weight of the holdfast (HWT) was taken. All weights were taken as damp weights. These measurements were then used to determine if plant shape varied with depth and species using a multivariate statistical technique called Principal Components Analysis (PCA). Each individual measurement for each plant. HWT was removed from analysis as small amounts of bedrock were stuck to the holdfast therefore inflating that measurement in some plants. The resulting data set was then imported into PRIMER (Plymouth Routines in Multivariate Ecology) and subjected to PCA analysis. The aim of this was to produce an ordination plot resembling how the two *Laminaria* species changed shape with and depths and to determine which variables were important in producing the plot (Zuur, Ieno & Smith, 2007).

Once all measurements had been made, thin slices were made from the stipe of *Laminaria hyperborea* to determine plant age. The method used was that of Kain and Jones (1963) who showed that rings of growth would be produced annually in *Laminaria hyperborea,* and these could be viewed and counted in thin sections to age the plants (Figure 5b). Samples were then collected from the tissues and processed for biochemical analysis.

In addition to the metrics above, which were then used to determine if the plants varied in overall shape with depth of water and species, we also scored each plant for grazing or scouring damage and any signs of bleaching or blistering of the lamina. At the time of sampling, no blistering or bleaching of the specimens was observed and both grazing and scouring damage was minimal.

3.4.4 Sample storage

Dried samples were stored in sealed plastic bags for three months before biochemical analysis. Holdfast specimens including associated animal fauna were frozen for later analysis.

3.4.5 Biochemical analysis

Samples of tissue for carbon, hydrogen and nitrogen (CHN) analysis were taken once morphometric measurements had been completed. For each plant, a 3 cm x 3 cm square of tissue was removed from the meristem area, the middle and the end of the lamina (to account for changes in tissue levels with lamina age) and a section of the stipe to determine if CHN varied between species and site. Superficial water was removed from the samples to obtain a fresh weight (FW) of tissue, and then drying was done in an oven at 50°C for 48 hrs to a constant dry weight (DW) and then re-weighed. These samples were then processed for CHN measurements.

Data on carbon contents of kelp tissue from CHN analysis compared with values in the literature and a high degree of similarity was found, confirming accuracy of our analysis (Table 5)

Table 5 Comparison of carbon quantities contained within different kelp species tissues derived from CHN analysis and those published in the literature.

Species	Reference	Location	Carbon content
Laminaria hyperborea	Pessarrodona et al. 2018	SW England	31.2%
	Sjotun et al. 1996	Norway	31.3%
		Mean:	**31.3%**
	Present study	Yorkshire	33.0%
Laminaria digitata	Gevaert et al. 2008	N France	29.1%
	Brady-Campbell et al. 1984	Rhode Island	26.9%
	Mann 1972	Nova Scotia	32.7%
		Mean:	**29.6%**
	Present study	Yorkshire	30.3%
Saccharina latissima	Brady-Campbell et al. 1984	Rhode island	31.5%
	Gevaert et al. 2001	N France	28.0%
		Mean:	**30.0%**
	Present study	Yorkshire	27.7%

3.4.6 Stable isotope analysis

Sub-samples of collected kelps were sent to the University of Durham for analysis of the stable isotopic composition of carbon and nitrogen.

3.4.7 Biomass to carbon conversions

Fresh weight (FW) biomass measures of each kelp species were first converted to dry weight (DW). In order to do so, values for the ratio between DW and FW (DW:FW) were calculated. Small sections of blade material from each species were weighed (FW), dried in an oven at 60°C for 48hrs and re-weighed (DW). Additional values for DW:FW were sought from the literature for *Laminaria digitata* (0.155) (Gevaert et al., 2008) and *Saccharina latissima* (0.113) (Gevaert et al., 2001), as well as for *Laminaria hyperborea* stipes (0.21) (Smale et al., 2020b) and holdfasts (0.191) (Jupp & Drew, 1974). Combined with the data collected here on blade tissue DW:FW, a set of final whole-individual DW:FW values were calculated for each species to be used in the conversion of FW biomass values into DW biomass. Data on the proportion of carbon contained within kelp tissues derived from CHN analysis (described above) could then be used in the conversion of DW biomass to carbon quantities per individual kelp.

The quantity of carbon stored in each kelp species was then statistically analysed using univariate analysis of variance (ANOVA) to test for variations between the sampled sites for each species. All analysis and data visualisation were carried out in RStudio (RStudio Team, 2022) using the packages Car (Fox et al., 2001) and ggplot2 (Wickham, 2016).

Estimates of annual production were calculated through the conversion of blade FW biomass to carbon quantities via the above-described method. This was done for two species of kelp, *L. digitata* and *L. hyperborea,* since these species follow the same growth pattern whereby old-growth lamina material is released and shed into the surrounding environment each year between March and May in a phenomenon termed 'May cast' (Pessarrodona et al., 2018)

3.4.8 Satellite ocean colour remote sensing

Multispectral cameras onboard earth-orbiting satellites can capture information at high spatial resolution on blue carbon habitats. For example, seagrass extent across Europe has been mapped in detail by using the imager carried by the Sentinel-2 satellite, with four bands at different parts of the spectrum (blue, green, red and infrared) producing images at 10m resolution (Zoffoli et al., 2021, 2020). Mapping intertidal seaweeds such as *Fucus*, and intertidal seagrass zones can be done with accuracy using remote sensing, as pixels in scenes captured at low tide are not obscured by overlying water. Extent of beds for very large kelps such as the giant kelp (*Macrocystis pyrifera*) can also be done accurately, as the floating fronds of the kelp form a dense mat at the sea surface (Timmer et al., 2022, 2024). Infrared bands are particularly useful for classifying kelp, as sunlight is absorbed strongly by water, but reflected strongly by kelp fronds at these wavelengths. Underwater kelp forests are more challenging to map via remote sensing, as clear water conditions are required in order to allow sunlight to reach the kelp canopy and return to the ocean surface. In practice, satellite remote sensing in the waters around the UK is restricted to times when low tide and clear water conditions coincide with the midday satellite overpass. Such conditions are rare and systematic searching of satellite image archives was required in order to detect a scene captured under the best viewing conditions.

Sentinel-2A scene from 24/06/2024 was retrieved from the image archive at *https://browser.dataspace.copernicus.eu/*. With prior knowledge of the maximum kelp depth range from underwater video surveys (see later), a mask from 2 m to -5 m depth was applied to the image to restrict size and increase processing speed. The green band was isolated, as this colour penetrates deepest in coastal waters, and reflectance values were extracted for each of a series of *in situ* video sampling points, that were scored as individual kelp plants per m^2 as described above (during conversion from SACFOR scale estimates, high values were capped at 5 individuals m^2 maximum).

To classify the image, a random forest (RF) model was generated using the 'randomForest' R package (ntree = 500). A RF model is a supervised classification based on decision trees, trained with in situ data to allow extrapolation on entire satellite tiles. Two-thirds of the extracted values were used to train the model (78 values), and the remaining third was used for validation (39 values).

4 Results

4.1 Kelp photophysiology

Measurements of algal physiological status were made for intertidal and subtidal specimens of the three main kelp species. Measurements were restricted to the actively growing meristem region of the main blade. Across the study, the maximum photosynthetic efficiency of photosystem II (F_v/F_m) was highest for *L. hyperborea* with a mean value of 0.702 (+/- 0.071) followed by L. digitata with 0.669 (+/- 0.049) and *S. latissima* with the lowest average of 0.655 (+/-0.068). Values of F_v/F_m of over 0.65 generally indicate that the algal material is photosynthetically-competent and not impacted by environmental stress (high irradiance, nutrient deficiency, high temperature). The highest F_v/F_m values were observed in *L. hyperborea* collected by diving from the subtidal kelp forest (Figure 6). Maximum rates of electron transport were similar between all species and across sites, with a tendency for samples from deeper water to show a higher ETR_{max}. Work is ongoing to compare photosynthetic rates between kelps and neighbouring fucoid populations. Light saturation points (E_k) varied in a narrow range between 90 umol photon m^{-2} s^{-1} for *S. latissima*, 115 umol photon m^{-2} s^{-1} for *L. digitata* and 119 umol photon m^{-2} s^{-1} for *L. hyperborea*. These are relatively low values in comparison with the more high-light acclimated fucoid assemblages that typically light-saturate at over 300 umol photon m^{-2} s^{-1}.

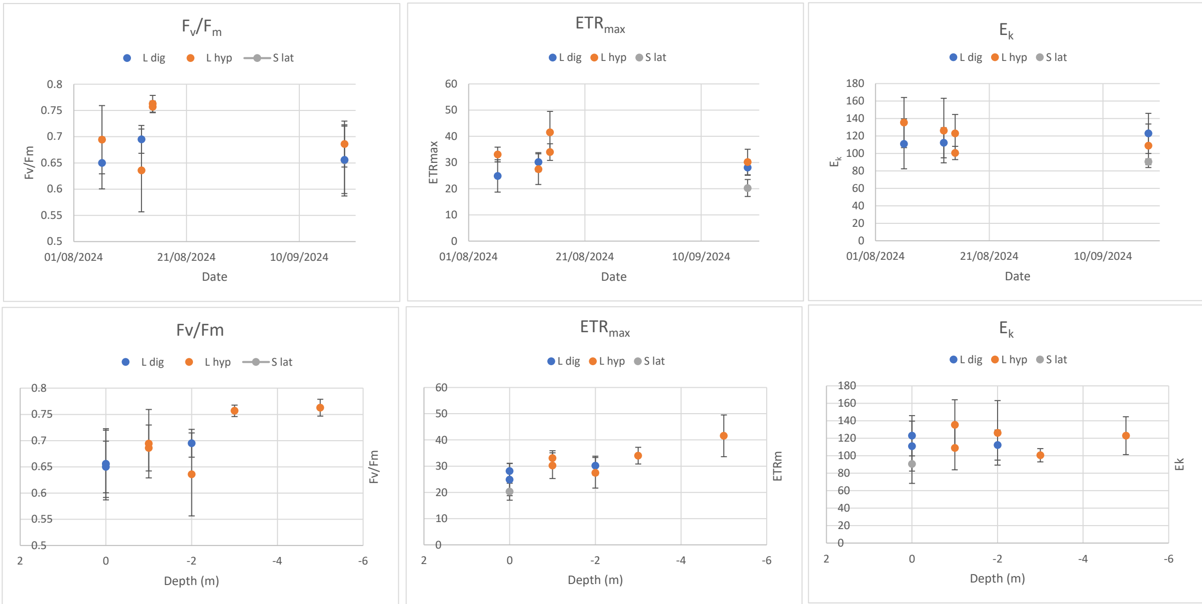


Figure 6 Summary of photosynthetic measurements on kelp blade material for the three main kelp species Laminaria hyperborea, Laminaria digitata and Saccharina latissima.

4.2 Kelp biometrics

The PCA plot showing the relative clustering of each individual plant according to the overall shape is presented in Figure 7. From the figure, it is apparent that *Laminaria digitata* appears as a separate cluster to the left of the plot whilst *Laminaria hyperborea* form a looser cluster of points more to the right of the plot. Depth (denoted by colour on the plot with dark blue being sublittoral plants and pale blue intertidal) appears to show a separation too, with both species showing a scatter of points that resembles a separation due to depth of collection (Figure 7). The two species are separated along the x-axis by PCA1 and in this case. The separation of the two species is mainly the result of the length of the lamina against the weight of the stipe, with plants to the left of the figure having longer lamina (LL) relative to the weight of the stipe (SWT). PCA2 (y-axis) reflects the change in shape with depth in the two species, with the sublittoral plants having greater lamina weights (LWT) relative to the weight of the stipe (SWT). Overall, *Laminaria digitata* has a longer lamina compared to stipe weight than does *L. hyperborea* and both species show a reduction in stipe weight (SWT) against lamina weight (LWT) in shallow water.

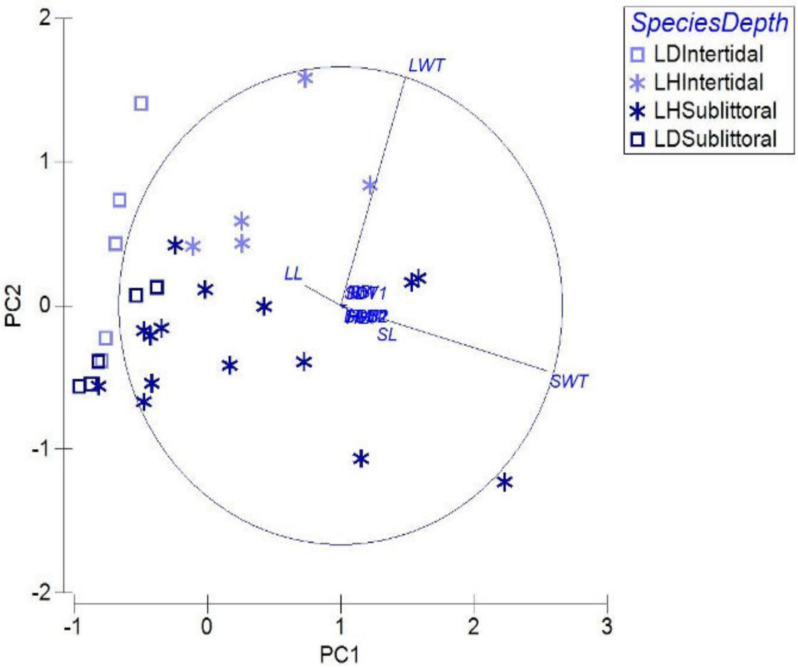


Figure 7 PCA plot generated from the morphometric data of two kelp species showing the separation of Laminaria digitata from Laminaria hyperborea on PCA1 axis, and the separation of both species by depth on the PCA2 axis. For explanation see text.

4.3 Intertidal kelp density, grazer abundance and community structure

There was a marked difference in kelp abundance between the five shores sampled (see Figure 8a below). All species were rare at South Landing with very few plants found within the intertidal, however *Laminaria hyperborea* was visible at low water further out in the sublittoral zone. *Saccharina latissima* was the most abundant species on that shore, but at very low densities and *Laminaria digitata* was only represented by a few individuals across all quadrats. There was no evidence of any regeneration in the form of sporelings on the shore. This is in marked contrast to Selwicks Bay where *L. digitata* was abundant on the shore and lots of *Laminaria* sporelings were observed in the quadrats. Both *L. hyperborea* and *S. latissima* were present but at low densities. This pattern was repeated at Filey Brigg, Boggle Hole and Runswick Bay, with all three species present on the shore and clear evidence of regeneration of the populations evident with lots of sporelings present (Figure 8A).

The predominant grazer densities per 1m^2 quadrat are illustrated in Figure 8B. By far the most abundant was the blue-rayed limpet (*Patella pellucida*) that was present in large numbers at North Landing and Filey where it was found on both plants and bedrock, however it was less common in the more northern sites (Boggle Hole and Runswick). It was totally absent from South Landing as its main food supply (predominantly *Laminaria*) was absent. The northern pink limpet (*Tectura virginea*) occurred where the bedrock was covered by encrusting red algae and was absent from South Landing and a similar pattern was observed for patellid limpets (both *Patella vulgata* and *Patella ulyssiponensis*) (Figure 8B). Interestingly, the number of damaged stipes/holdfasts was greatest on shores where blue-rayed limpets occur in high densities, indicating that these specialist grazers could be the cause of the plant loss.

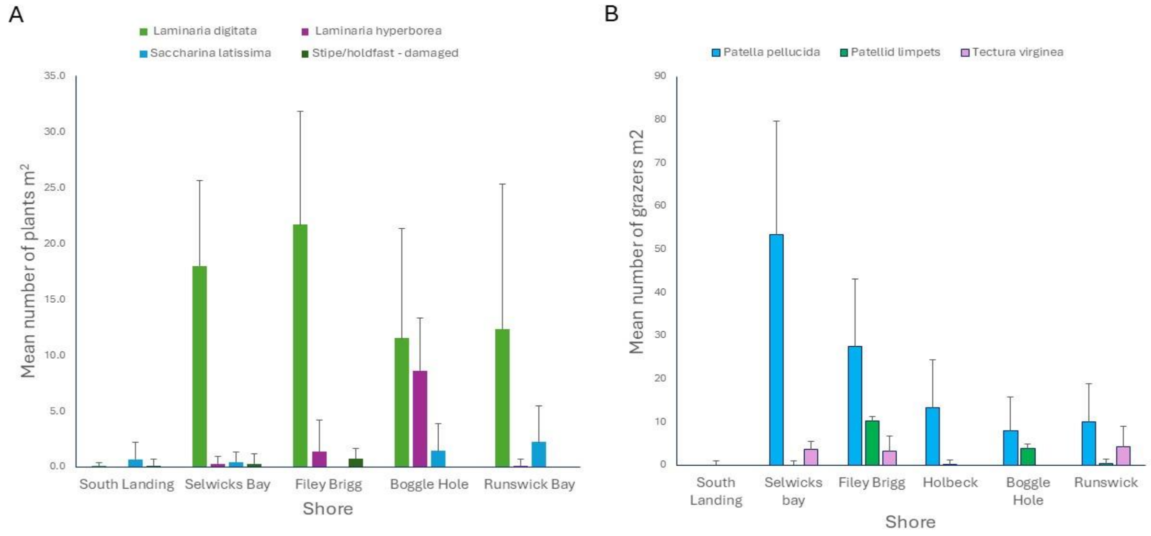


Figure 8 Description of mean density (+SD) m2 of A) the different species of kelp plus damaged plants and B) the number of grazers found in the intertidal quadrats from the different shores.

Overall, there were marked differences in encrusting fauna and flora community structure associated with intertidal kelp between shores, with samples from South Landing (purple asterisks) and Runswick Bay (blue open diamonds) forming discrete clusters on the MDS plot shown in Figure 9. These communities appear to be very different in terms of their similarity in community composition, with South Landing being dominated by the red algae sand binder (*Rhodothamniella floridula*) and very little kelp present, whereas the other shores all had mature plants. There was no clustering of the quadrats by rock type, as both chalk shores (Selwicks Bay and South Landing) were separate from each other and have no overlap, with both mudstone shores (Runswick Bay and Boggle Hole) also showing little overlap and Holbeck being different to Filey. Overall, the ANOSIM test showed that there was a significant difference in community similarity between the shores (ANOSIM, $R=0.834$, $P<0.01$) and after pairwise comparisons it was shown that each shore was significantly different to the rest in terms of community similarity ($P<0.05$).

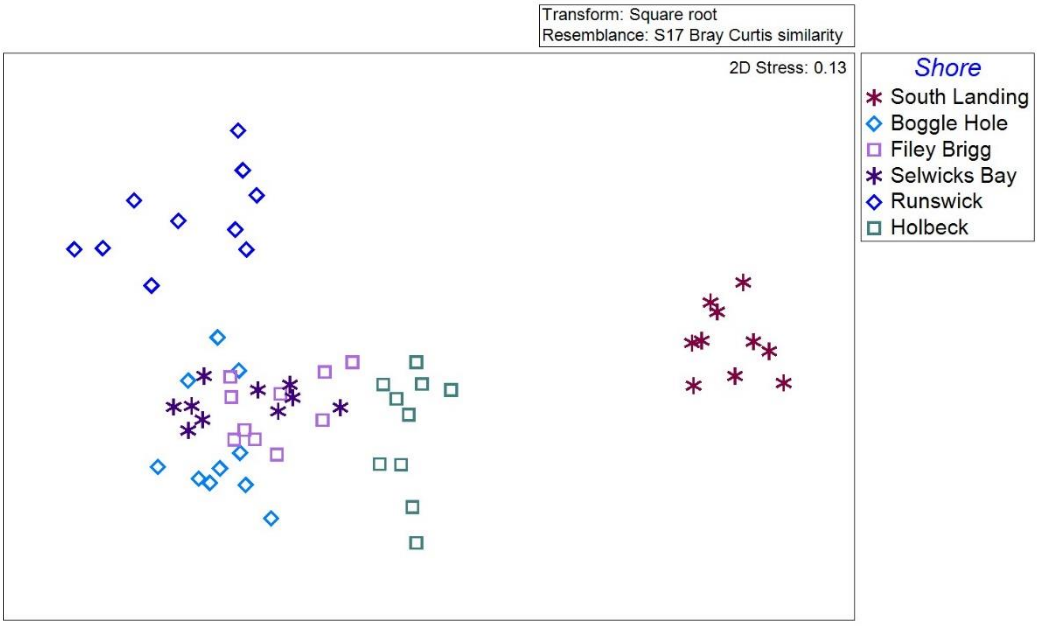


Figure 9 An ordination plot generated from MDS (multi-dimensional scaling) that shows the clustering of each encrusting species kelp bed intertidal quadrat sample relative to the other samples from the different shores. The plot is a good representation of the data as the stress level =0.13).

The SIMPER analysis revealed that the distinctive nature of the South Landing quadrats was determined by the high abundance of *Rhodothamniella floridula*, *Taonia atomaria* and *Ceramium* sp./ *Polysiphonia* sp. resulting in an overall 69% similarity between the quadrats across the shore. The same species, alongside the lack of *Laminaria digitata* and red encrusting algae were the main reason this site was so different to all the others, with South Landing being over 80% dissimilar to all other sites. Whilst *R. floridula* was abundant at Holbeck (average similarity between quadrats 71%), this shore also had good *Laminaria spp*. cover and therefore clustered with the other kelp rich shores. These shores had abundant kelp cover with varying abundances of encrusting algae or *R.floridula*, creating communities that are similar in terms of species present but vary in terms of the individual abundance of the species present (Figure 10).

Apart from the obvious fact of very little kelp found at South Landing creating a distinctive community on that shore, the presence and absence of rarer species within the intertidal communities was one of the main reasons for the differences in similarity between shores. Table 7 is a presence / absence table of the different species found at each site to illustrate how the species present form unique intertidal communities across the region. The lowest number of species found was at South Landing with 28 species found. Despite this, 5 of those were only recorded at that particular site including beautiful eyelash weed (*Calliblepharis ciliata*) and dotted peacock weed (*Taonia atomaria*). A higher richness was found at Selwicks Bay, and the highest number of species found in a kelp bed was at Filey Brigg, where 55 species occurred. Holbeck has large scale sand movement on and off the shore across the kelp bed, one possible reason why richness was comparatively lower here. Both the mudstone shores in the north of the region have over 50 species recorded during the surveys, with both Runswick and Boggle Hole supporting one unique species not recorded elsewhere during the study (*Oshurkovia littoralis*) (Table 6).

Table 6 Presence-absence table to show the species present on each shore in the kelp bed intertidal communities pale blue cells indicate presence at site, black indicates absence.

Phylum or Class	Common name	Scientific name	South Landing	Selwicks bay	Filey Brigg	Holbeck	Boggle Hole	Runswick
	Slimy whip weed	*Chordaria flagelliformis*	Absent	Absent	Absent	Absent	Absent	Present
	Hairy sand weed	*Cladostephus spongiosus*	Present	Present	Present	Present	Present	Present
	Brown fan weed	*Dictyota dichotoma*	Absent	Absent	Absent	Absent	Absent	Present
		Ectocarpus sp	Absent	Absent	Absent	Absent	Absent	Present
	Serrated wrack	*Fucus serratus*	Present	Present	Present	Present	Present	Present
		Fucus sporelings	Absent	Absent	Absent	Present	Present	Absent
Phaeophyta	Thongweed	*Himanthalia elongata*	Absent	Absent	Present	Absent	Absent	Absent
	Oarweed	*Laminaria digitata*	Present	Present	Present	Present	Present	Present
	Cuvie	*Laminaria hyperborea*	Absent	Present	Present	Present	Present	Absent
		Laminaria sporelings	Absent	Present	Present	Present	Present	Present
	Pylaies brown filaments	*Pylaiella sp.*	Present	Absent	Absent	Absent	Absent	Absent
	Sugar kelp	*Saccharina latissima*	Present	Present	Present	Present	Present	Present
	Dotted Peacock weed	*Taonia atomaria*	Present	Absent	Absent	Absent	Absent	Absent
	Green hair weed	*Cladophora rupestris*	Absent	Present	Present	Absent	Present	Present
		Cladophora sp.	Absent	Absent	Present	Present	Present	Absent
Chlorophyta	Sea lettuce	*Ulva lactuca*	Present	Absent	Present	Absent	Present	Absent
	Ribbon weed	*Ulva linza*	Present	Absent	Absent	Absent	Absent	Absent
	Ridgid sea lettuce	*Ulva ridgida*	Absent	Absent	Present	Present	Absent	Present
		Ulva sp.	Absent	Present	Absent	Absent	Absent	Present
	Black Scour weed	*Ahnfeltia plicata*	Absent	Present	Present	Present	Present	Present
	Beautiful eyelash weed	*Calloblepharis ciliata*	Present	Absent	Absent	Absent	Absent	Absent
		Ceramium shuttleworthiana	Absent	Absent	Present	Absent	Absent	Absent
	Pincer weed	*Ceramium sp*	Present	Present	Present	Present	Present	Present
	Irish Moss	*Chondrus crispus*	Present	Present	Present	Present	Present	Present
	Coralweed	*Corallina officinalis*	Absent	Present	Present	Present	Present	Present
	Fine-veined crinkle weed	*Cryptopleura ramosa*	Present	Absent	Present	Absent	Present	Present
	Purple claw weed	*Cystoclonium purpureum*	Present	Present	Present	Present	Present	Present
	Sea beech	*Delesseria sanguinea*	Present	Absent	Absent	Absent	Present	Absent
	Red rags	*Dilsea carnosa*	Absent	Absent	Absent	Present	Present	Absent
	Clawed fork weed	*Fucellaria lumbricalis*	Absent	Present	Absent	Present	Absent	Absent
	Under tongue weed	*Hypoglossum hypoglossoides*	Present	Absent	Absent	Absent	Absent	Absent
	Bunnys ears	*Lomentaria articulata*	Absent	Absent	Present	Present	Present	Absent
	False Irish Moss	*Mastocarpus stellatus*	Absent	Present	Present	Present	Present	Present
		Mastocarpus tetrosporophyte	Absent	Absent	Absent	Present	Absent	Absent
Rhodophyta	Winged weed	*Membranoptera alata*	Present	Present	Present	Present	Present	Present
	False pepper dulse	*Osmundea hybrida*	Absent	Present	Absent	Absent	Present	Absent
	Royal fern weed	*Osmundea osmunda*	Present	Present	Absent	Present	Present	Absent
	Pepper dulse	*Osmundea pinnatifida*	Present	Present	Present	Absent	Present	Absent
	Dulse	*Palmaria palmata*	Present	Present	Present	Absent	Absent	Present
	Sea Oak	*Phycodrys rubens*	Absent	Absent	Absent	Absent	Present	Absent
	Leafy sand binder	*Phyllophora pseudoceranoides*	Present	Absent	Present	Absent	Present	Absent
		Pink crust	Absent	Present	Present	Present	Present	Present
	Lyngbyes cocks comb	*Plocamium lyngbyanum*	Absent	Present	Absent	Present	Present	Present
	Magg's cock comb	*Plocamium maggsiae*	Present	Absent	Present	Present	Present	Present
	Soft feather weed	*Plumaria plumosa*	Absent	Present	Present	Present	Present	Present
		Polysiphonia sp	Absent	Present	Present	Present	Present	Present
	Black siphon weed	*Vertebrata fucoides*	Present	Absent	Absent	Absent	Absent	Absent
		Red crust	Absent	Absent	Absent	Present	Absent	Absent
	Straggly bush weed	*Rhodomela confervoides*	Absent	Absent	Absent	Absent	Present	Present
	Sand binder	*Rhodothamniella floridula*	Present	Present	Present	Present	Present	Present
	Breadcrumb sponge	*Halichondria panicea*	Absent	Present	Present	Present	Present	Present
Porifera	Slimy sponge	*Halisarca dujardini*	Absent	Present	Present	Present	Present	Present
		Hymeniacidon perleve	Present	Absent	Absent	Absent	Absent	Absent
		Celleporella hyalina	Absent	Absent	Absent	Present	Present	Present
		Electra pilosa	Present	Present	Present	Present	Present	Present
Bryozoa		*Membranipora membranacea*	Absent	Present	Present	Present	Present	Present
		Conopeum reticulum	Absent	Absent	Present	Absent	Absent	Absent
		Escharoides coccinea	Absent	Absent	Present	Absent	Absent	Absent
		Oshurkovia littoralis	Absent	Absent	Absent	Absent	Present	Present
	Star sea squirt	*Botryllus schlosseri*	Absent	Absent	Absent	Absent	Absent	Present
Tunicata		*Morchellium argus*	Present	Absent	Absent	Absent	Absent	Absent
	Beadlet anemone	*Actinia equina*	Absent	Absent	Present	Present	Absent	Absent
Cnidaria	Dahlia anemone	*Urticina felina*	Absent	Absent	Present	Absent	Present	Absent
		Dynamena pumila	Absent	Present	Present	Present	Present	Present
		Balanus crenatus	Absent	Absent	Absent	Absent	Present	Present
	Green shore crab	*Carcinus maenas*	Absent	Absent	Absent	Present	Absent	Absent
	Velvet swimming crab	*Necora puber*	Absent	Absent	Absent	Absent	Absent	Present
	Hermit crab	*Pagurus bernardus*	Absent	Absent	Present	Absent	Present	Present
Arthropoda		*Pilumnus hirsuitus*	Absent	Absent	Absent	Present	Absent	Present
		Pirimela denticulata	Absent	Absent	Absent	Absent	Absent	Present
	Long-clawed prcelain crab	*Pisidia longicornis*	Absent	Absent	Absent	Present	Absent	Present
	Acorn barnacle	*Semibalanus balanoides*	Absent	Absent	Present	Absent	Present	Absent
	Wart barnacle	*Verruca stroemia*	Absent	Absent	Present	Present	Present	Present
Mollusca		*Anomia ephippium*	Absent	Present	Present	Absent	Absent	Present
	Grey top shell	*Steromphala cineraria*	Absent	Present	Present	Absent	Present	Present
	Chink shell	*Lacuna vincta*	Absent	Absent	Present	Absent	Absent	Absent
		Lepidochitona cinerea	Absent	Present	Present	Absent	Absent	Absent
	Flat periwinkle	*Littorina fabalis*	Absent	Absent	Present	Absent	Absent	Absent
	Blue mussel	*Mytilus edulis*	Absent	Absent	Present	Absent	Present	Absent
		Nassarius reticulatus	Present	Absent	Absent	Absent	Present	Absent
	Dogwhelk	*Nucella lapillus*	Absent	Absent	Absent	Present	Present	Absent
	Blue-rayed limpet	*Patella pellucida*	Present	Present	Present	Present	Present	Present
	China limpet	*Patella ulyssiponensis*	Absent	Absent	Present	Present	Present	Present
	Common limpet	*Patella vulgata*	Absent	Absent	Present	Absent	Present	Absent
		Tectura virginea	Absent	Present	Present	Absent	Absent	Present
		Sabellaria spinulosa	Absent	Present	Present	Present	Present	Present
		Hydroides norvegica	Absent	Absent	Absent	Absent	Absent	Present
Annelida		*Polydora sp.*	Absent	Present	Absent	Absent	Absent	Absent
		Spirobis sp.	Absent	Present	Absent	Absent	Absent	Absent
	Keel worm	*Spirobranchus triqueter*	Absent	Present	Present	Absent	Present	Present
Echinodermata		*Amphipholis squamata*	Absent	Absent	Present	Present	Absent	Absent
Chordata	Shanny	*Lipophrys pholis*	Absent	Absent	Present	Absent	Absent	Absent
		Number of species	**28**	**39**	**55**	**44**	**54**	**50**
		Number of unique species	**5**	**0**	**0**	**1**	**1**	**1**

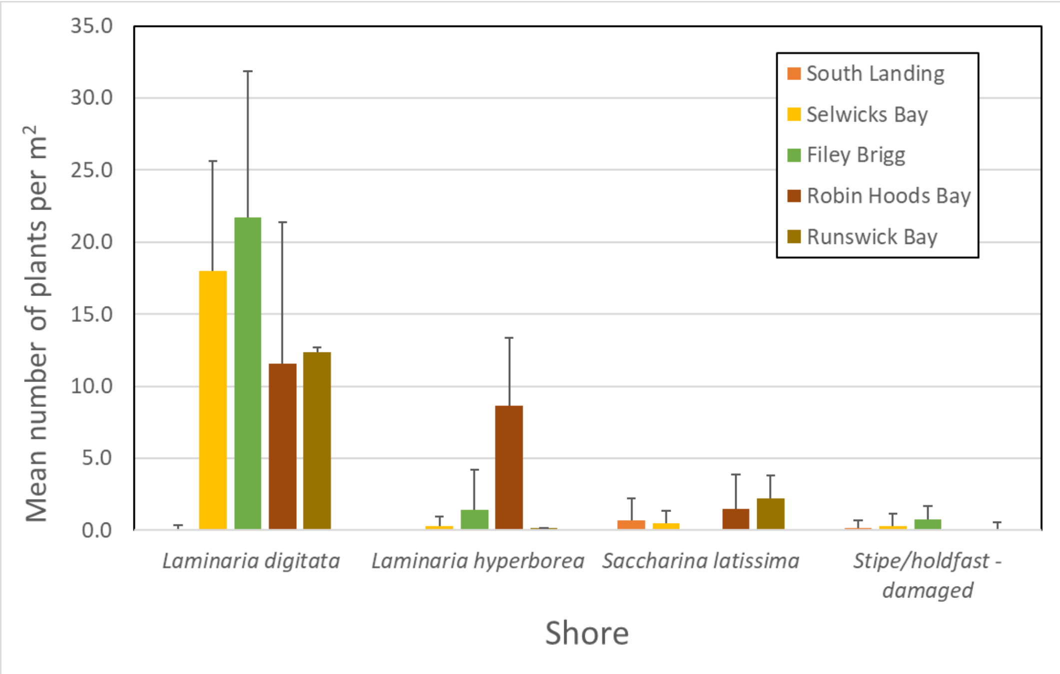


Figure 10 Density of kelps along low-shore intertidal belt transects during the summer of 2024.

4.4 Chemical analysis of kelp samples

4.4.1 Carbon quantities

Univariate ANOVA found no significant differences in the quantity of carbon stored within the tissues of each kelp species between the sampled sites (Table 7). In general, *Laminaria hyperborea* contained the greatest quantity of carbon within the average individual, with *Laminaria digitata* containing approximately one third of that of *L. hyperborea* (Figure 11). *Saccharina latissima* contained substantially smaller quantities of carbon per individual, likely an effect of this species generally having lower biomass than the larger *L. digitata* and *L. hyperborea* individuals.

A generic value of 30 g carbon per individual was taken forward to be used in estimation of the total Yorkshire coast carbon stock, representing the dominance of *L. hyperborea* across the region as a whole.

Annual estimates of carbon released to the surrounding environment from the shedding of blades from two species of kelp, *Laminaria digitata* and *Laminaria hyperborea* (Figure 12), found an average of 12.8g per individual for *L. hyperborea* and 14.2g per individual for *L. digitata*.

Table 7 Univariate ANOVA testing variability in carbon contents (g of carbon per individual) of different kelp species between sites on the Yorkshire coastline. Significant values(p<0.05) indicated in ***bold****.*

Species	Site			
	df	*F*	p	Res df
Laminaria hyperborea	3	0.72	0.550	26
Laminaria digitata	3	1.44	0.266	17
Saccharina latissima	2	1.08	0.366	14

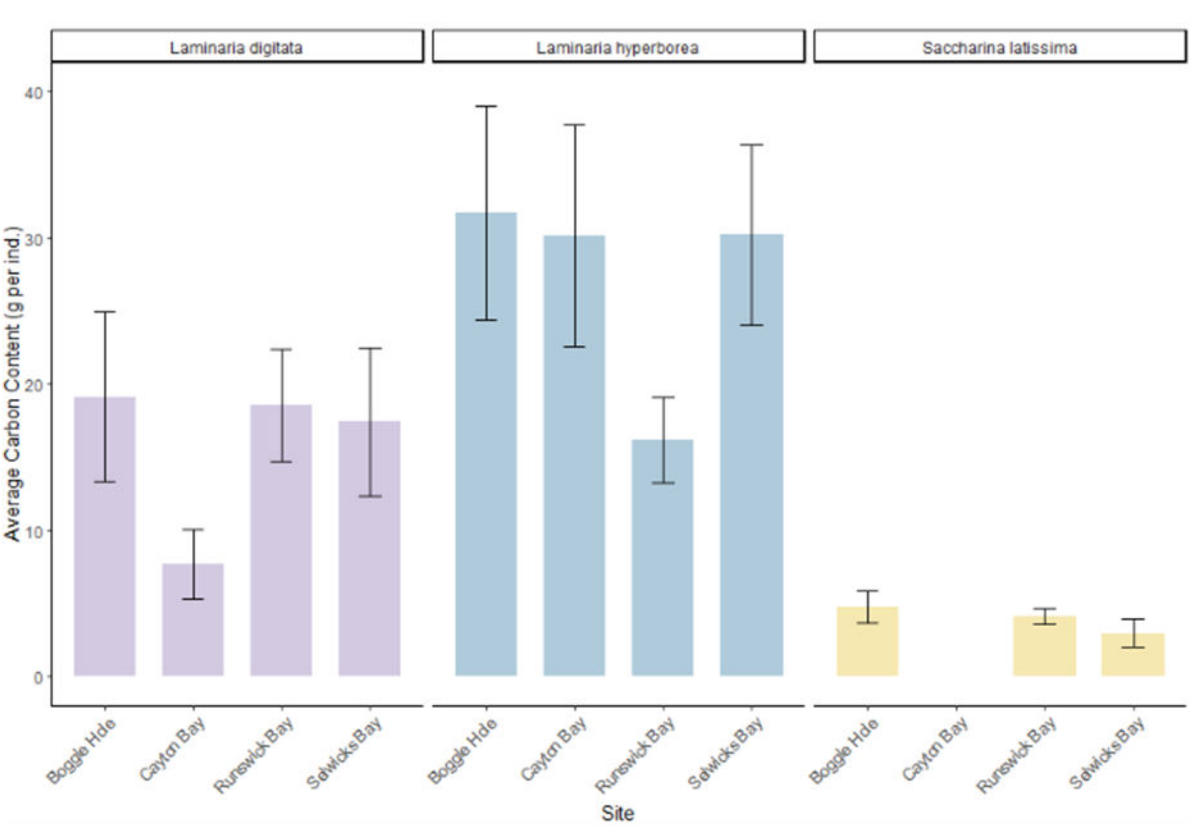


Figure 11 Average carbon content (g per individual) of three kelp species at sites on the Yorkshire coastline. Error bars represent standard error. n=5.

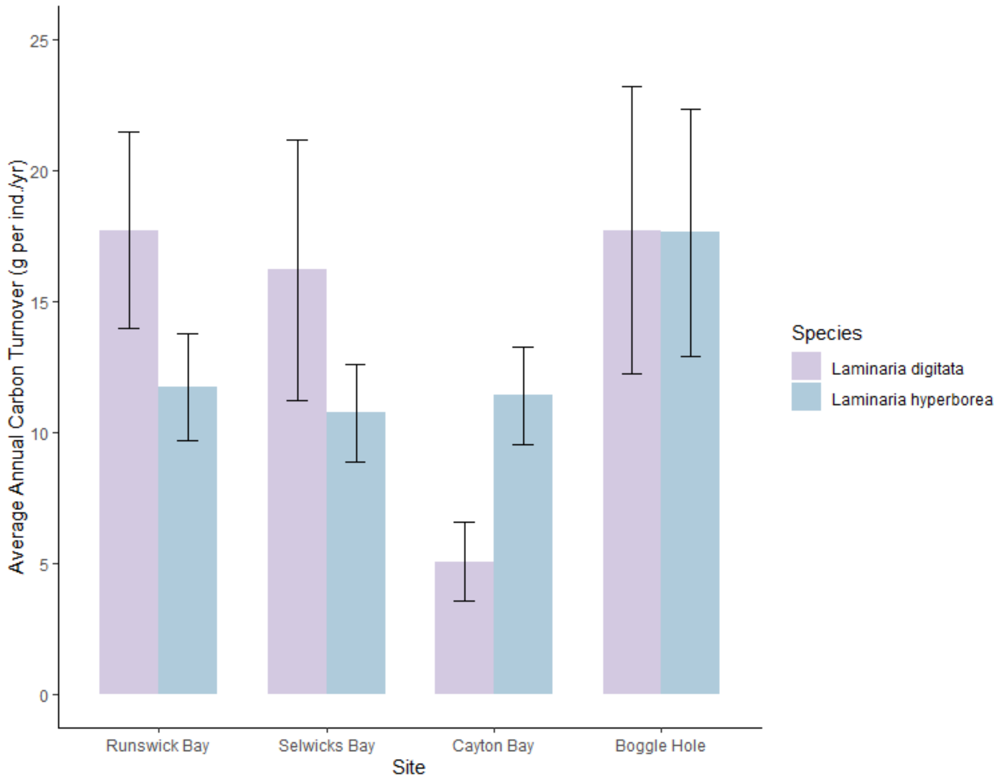
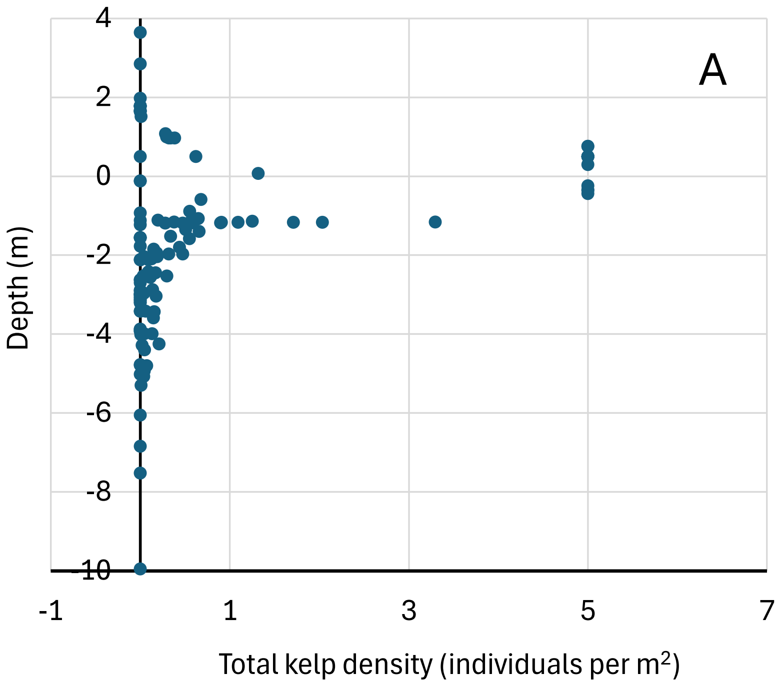


Figure 12 Annual estimate of carbon turnover derived from lamina loss in Laminaria hyperborea *and* Laminaria digitata *at sites on the Yorkshire coast. Error bars represent standard error. n=5.*

4.5 Kelp forest extent from underwater video

Underwater video coverage started at the shallowest depth to which the RIB could safely navigate, and this typically was 1.5 m. Hence, surveys done at high tide could begin a video transect over the intertidal zone and progressively quantify the kelp forest appearance at a depth equivalent to the mean low water of spring tides, through to its maximum density in the zone to -2 m, to a low-density zone from -2 to -4 m (Figure 13A). Very few kelp were detected in surveys below -5 m, even when suitable hard rock substrate was present (e.g. Figure 4). Depth below the surface is therefore a primary control on kelp abundance with a strong relationship being found between the natural logarithm of kelp density and depth (Figure 13B), analogous to the exponential decrease in underwater light with depth (Capuzzo et al., 2013). The extinction factor for kelp with depth was -0.9 m^{-1}, a value similar to extinction values for underwater light on the Yorkshire coastal waters[3].

[3] An average Secchi disc depth of 2 m, typical for coastal waters, would give an extinction coefficient of 1.7/2 = 0.9 m^{-1}.



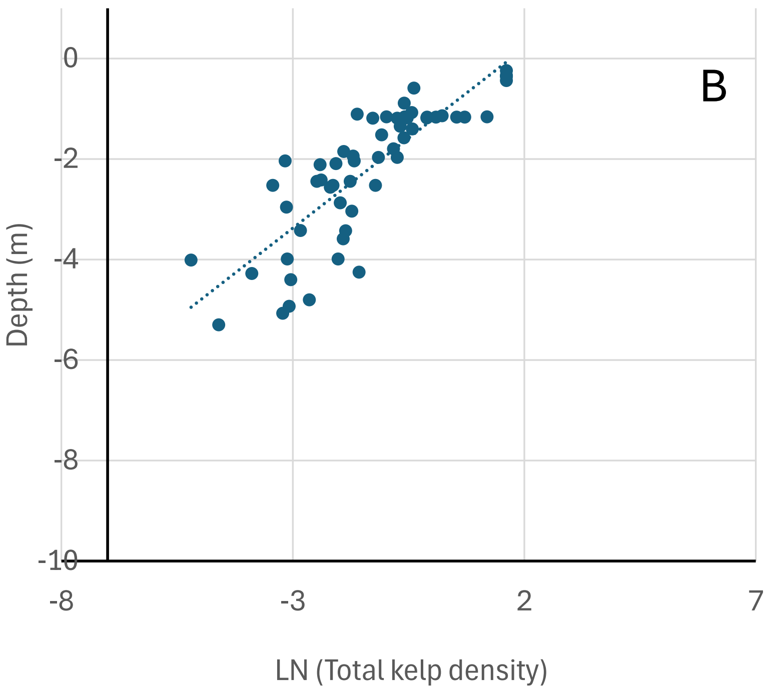


Figure 13 Total kelp density (all species; individuals per m^2) plotted as a function of depth for video survey transects in Section 1 (Staithes – Whitby). Depths are given relative to Chart Datum. A- Kelp density B – Natural logarithm of kelp density. The slope of the dotted line has a value of -0.9 m^{-1}.

4.6 Kelp biomass estimates from remote sensing

Video transect data was aggregated at one-minute intervals to give a mean count, and each count was geo-referenced and linked to a depth as described above. Plots of total kelp count data on maps of seabed habitat showed a strong association with rocky substrate in shallower areas. High kelp counts also appeared to correlate very well with dark-coloured patches visible on Sentinel-2 satellite images (examples are shown in Figure 14 and Figure 15). This opened the possibility for detailed mapping of kelp extent for the entire Yorkshire coast, including areas not surveyed.

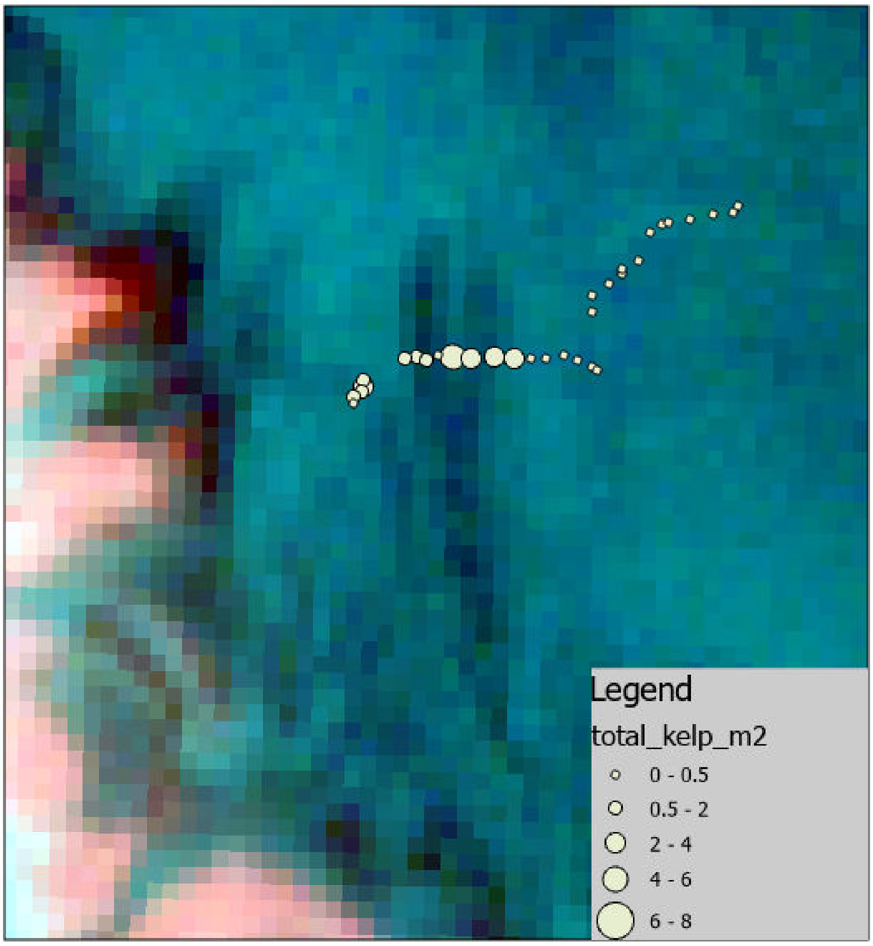


Figure 14 Overlay of kelp density estimate from video against satellite image of seabed features. Kelp forest patches show as darker blue colours against a lighter blue seabed.

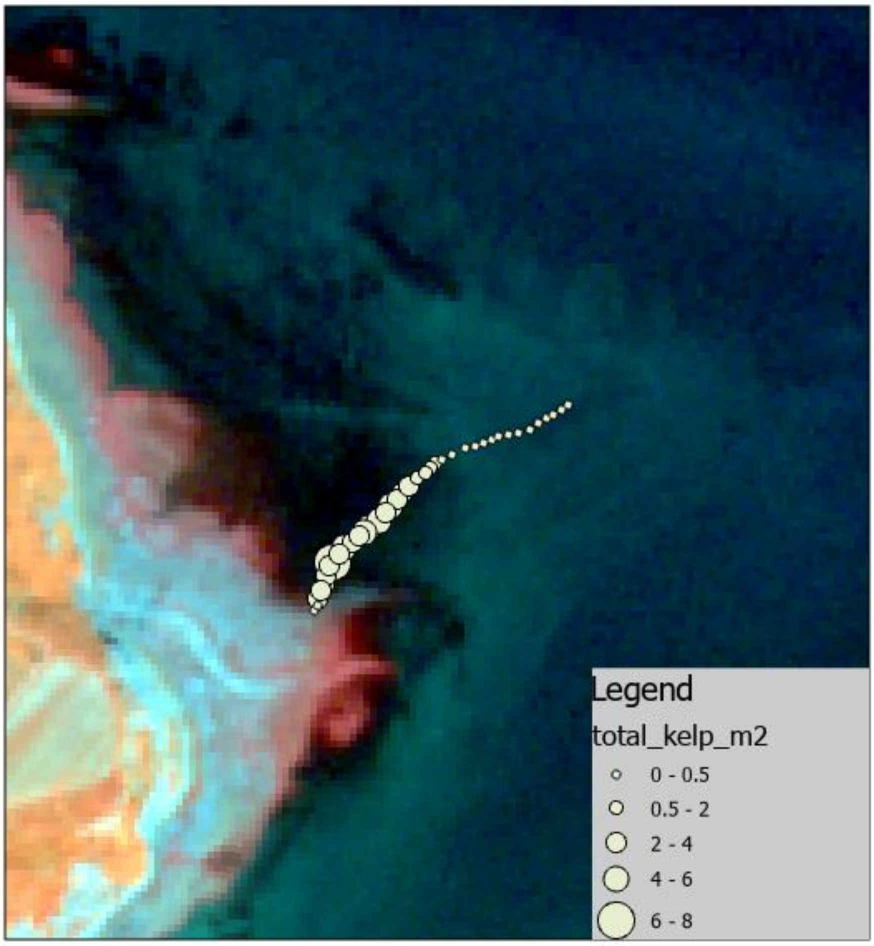


Figure 15 Overlay of kelp density estimate from video against satellite image of seabed features. Kelp forest patches show as darker blue colours against a lighter blue seabed.

A statistical model was constructed to compare the green-band satellite reflectance with kelp counts. The random forest technique performed with a RMSE of 1.77. The validation predicted vs ground truth gave a 0.84 correlation coefficient (r^2 = 0.7, Figure 16).

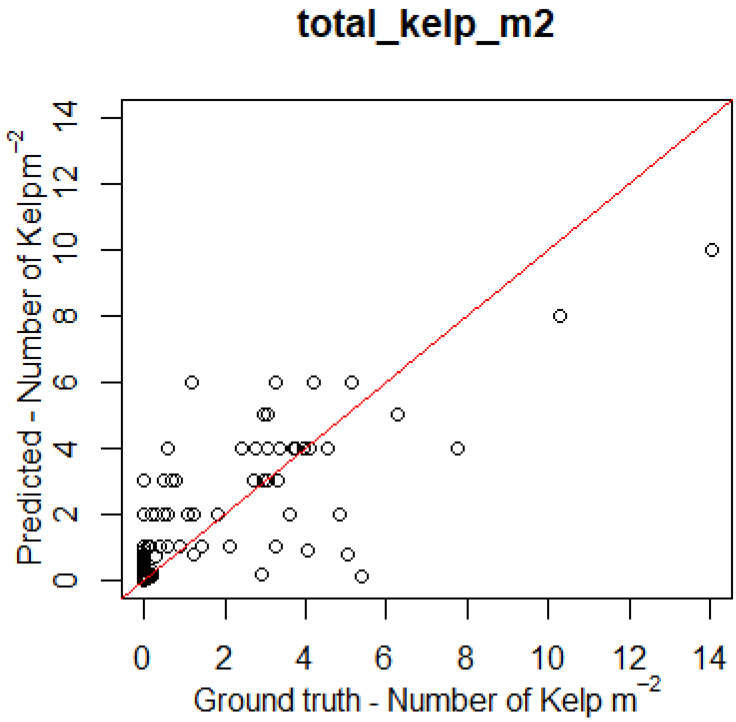


Figure 16 Validation of the random forest model for total kelp counts per m². The red line shows a 1:1 relation.

The coastal zone from Staithes to Filey Brigg was divided into equal units of area[4] as in Figure 17 and the total numbers of kelps, and conversion to standing stock of carbon (assuming a mean carbon per individual of 30 g) were calculated from the raster layer of modelled kelp density.

[4] Units had areas of 3 km by 3 km except unit 4 with 4 km by 3 km.

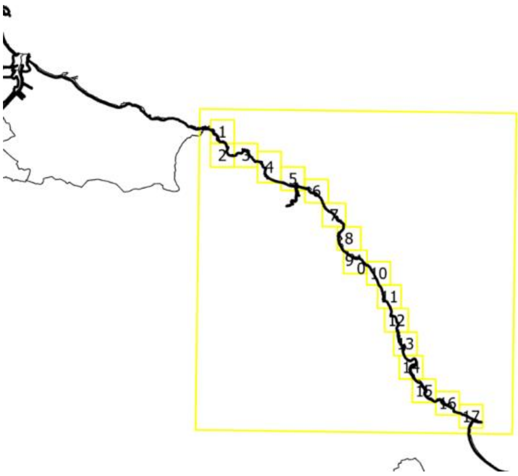


Figure 17 Zonation of Yorkshire coast from Staithes to Filey Brigg into seventeen squares for remote sensing kelp estimation.

Examples of detailed kelp mapping are shown in Figure 18 for the coastal squares 1 to 5, and the estimates of kelp density, standing stock of carbon and annual carbon fixation are given for each square in Table 8. The limit of the modelled area as -5 m as shown by the area marked blue in Figure 18, and kelp beds are shown with increasing brown coloration.

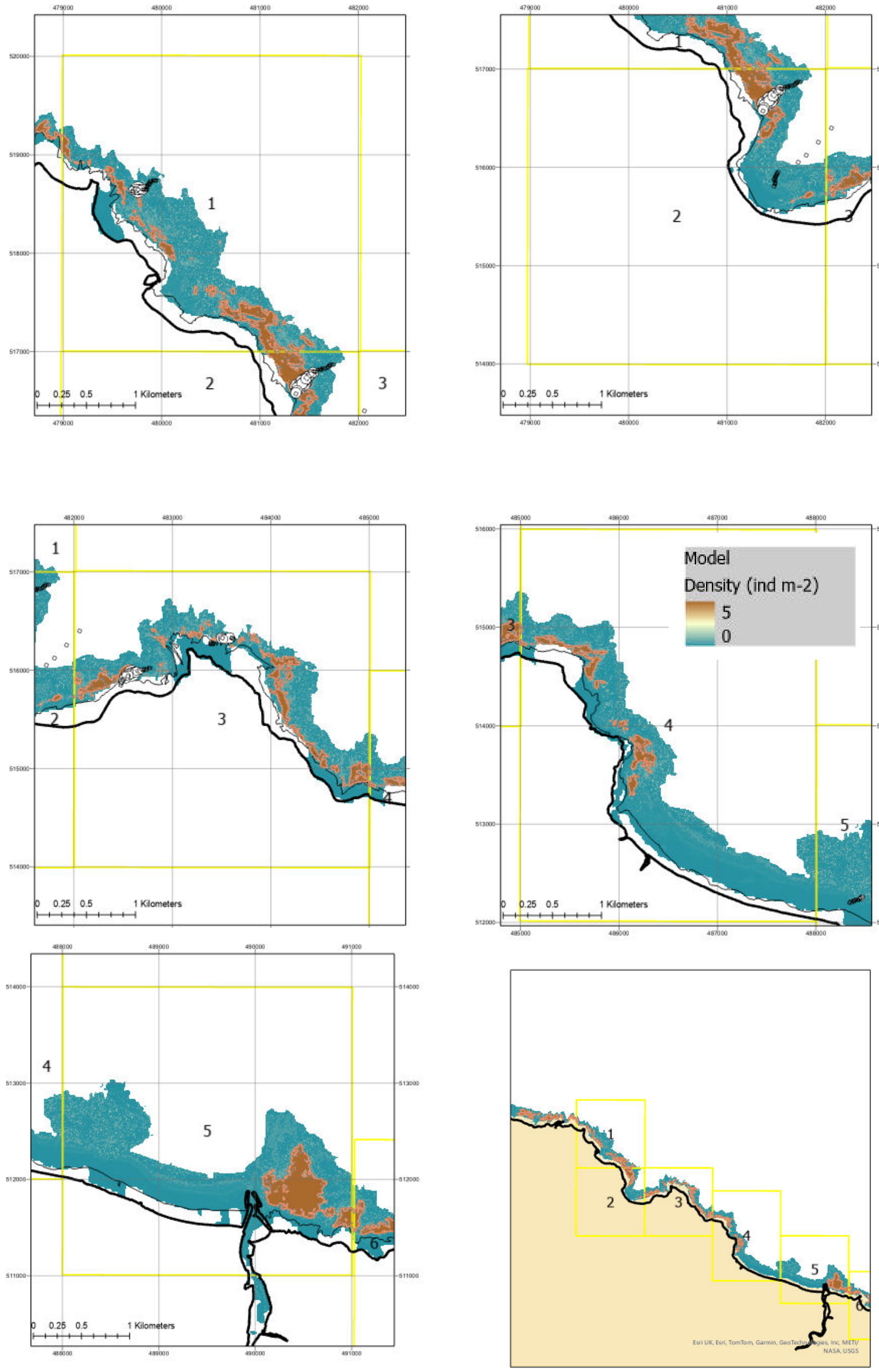


Figure 18 High-resolution kelp density mapping of the Yorkshire coast, from Staithes to Whitby, showing positions of high and low tide lines with thick and thin black lines. Locations of quantified video survey transects are shown with proportional symbols as overlay.

Zone 1, from Staithes to Port Mulgrave showed a linear (but interrupted) kelp feature parallel to the coast (Figure 18). The maximum width of the kelp forest was 250 m under the cliffs to the north of Runswick Bay, with an average horizontal extent of 120 m. A very large kelp bed of more than 1.5 km in length and with a width in places of more than 300 m extended across zones 1 and 2 and was most dense at the northern entrance to Runswick Bay. A 500 m video transect here captured the full extent of the kelp forest and showed excellent agreement with the satellite-based model. The central part of Runswick Bay itself had a seabed composed of either mobile sand or stones at depths of -5 to -10 m. No kelp was detected in this area. Linear, intermittent kelp beds with a narrow width extended from the south side of Runswick Bay through zones 3 and 4 to Sandsend Bay. Low concentrations of kelp were predicted for Sandsend Bay and confirmed by video. In Zone 5, the model showed there to be a very large kelp bed on sallow sublittoral rock immediately outside and to the east of Whitby harbour. Parts of the bed were visible at low tide as shown by an infrared/red vegetation index of the area in the summer of 2021 (Figure 19). There was a wider extent in the seaward direction of the low-tide-exposed kelp forest in 2021 compared to 2024. The model predicts that the highest concentration of kelp forest on the Yorkshire coast is located within Zone 5, at 169 tonnes C.

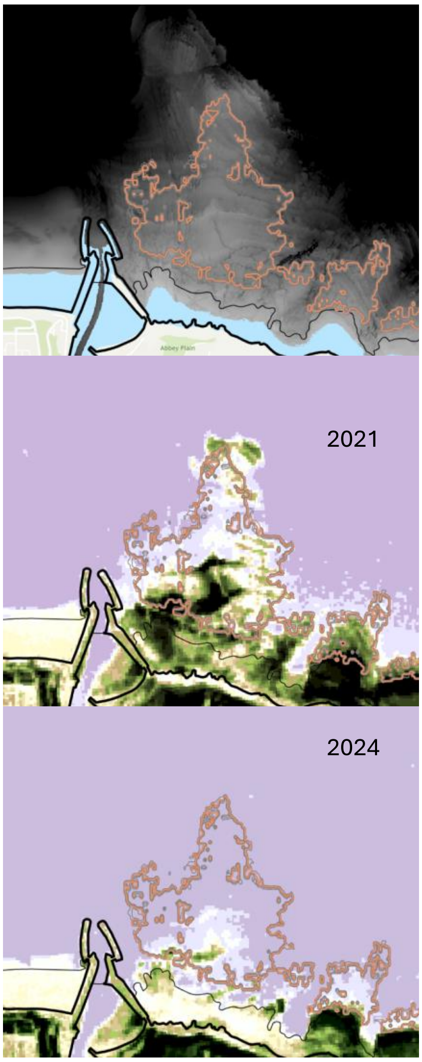


Figure 19 Difference in time for kelp coverage as exposed at low tide. shown by satellite-based vegetation index mapping. Upper panel: bathymetry of the rock platform to the east of Whitby harbour. Middle panel: Vegetation

index in August 2021. Lower panel: Vegetation index in June 2024. Contour lines indicate the predicted extent from modelling kelp density for the June 2024 image.

Zone 8, containing Robin Hood's Bay, contained the second highest kelp carbon stock at 159 tonnes. Zones 10 and 11 had the lowest kelp carbon stocks. Here, below the high cliffs of Ravenscar the bathymetry shows a steep gradient from shallow to deep water with little space for kelp. The presence of shallower subtidal rock in Zone 13 (Scalby) gave the third highest carbon stock at 150 tonnes in the 9 km^2 unit. Scarborough Headland in zone 14 had a low kelp biomass due to deep water close to shore, but zones 15 and 16, between Cayton Bay the start of Filey Brigg were intensively surveyed by video and had a shallower sloping bathymetry and consequently high kelp stocks at 108 and 133 tonnes of carbon, respectively.

Zone 17, containing Filey Brigg also held a low kelp stock. This was contrary to our prior assumptions that this site would have extensive offshore kelp coverage. There are dense lower intertidal *L. digitata* forests on Filey Brigg, but multiple video surveys revealed that the subtidal extent of *L. hyperborea* is strongly limited by deep water close to shore despite the presence of suitable hard substrate.

The best estimate at present for the Yorkshire coastal kelp standing stock of carbon in 2024, from Staithes to Filey Brigg is 1783 tonnes (Table 8). Calculations are in progress for the remaining section of rocky coast around Bempton and Flamborough Head. Initial estimate are for a further 250 tonnes of carbon stock for that zone. No kelp habitat is found south of Danes Dyke on Flamborough Head, or in the Humber, therefore a provisional total carbon stock for the whole Yorkshire coast can be given at approximately 2000 tonnes, to the nearest 100 tonnes.

The standing stock represents only the carbon that can be assessed at the time of survey and does not account for growth and loss of blade material during the year. A conservative estimate would give an additional 802 tonnes of carbon captured per year by the Yorkshire kelp forest (Table 8).

Table 8 Summed value for total kelp number (all species), total kelp carbon stock and annual turnover of carbon for the Yorkshire coastal units.

Zone	Location	Individual kelps	Carbon (tonnes)	Annual carbon turnover (tonnes)
1	Staithes – Port Mulgrave	4038845	121	55
2	Runswick Bay North	1735401	52	23
3	Runswick Bay East	3944200	118	53
4	Sandsend	4346540	130	59
5	Whitby	5618569	169	76

6	East of Whitby	25280 96	76	34
7	East of High Hawsker	27026 36	81	36
8	Robin Hood's Bay	53101 83	159	72
9	Ravenscar	32169 21	97	43
10	Cliffs south of Ravenscar	15311 38	46	21
11	Hayburn Beck	23569 17	71	32
12	East of Cloughton	31811 61	95	43
13	Scalby Mills	50056 56	150	68
14	Scarborough Head	34632 40	104	47
15	Osgodby / Cayton Bay	35966 86	108	49
16	North of Filey	44396 31	133	60
17	Filey Brigg	24181 64	73	33
Sum (ind or tonnes)		59,433 ,984	1783 t	802 t

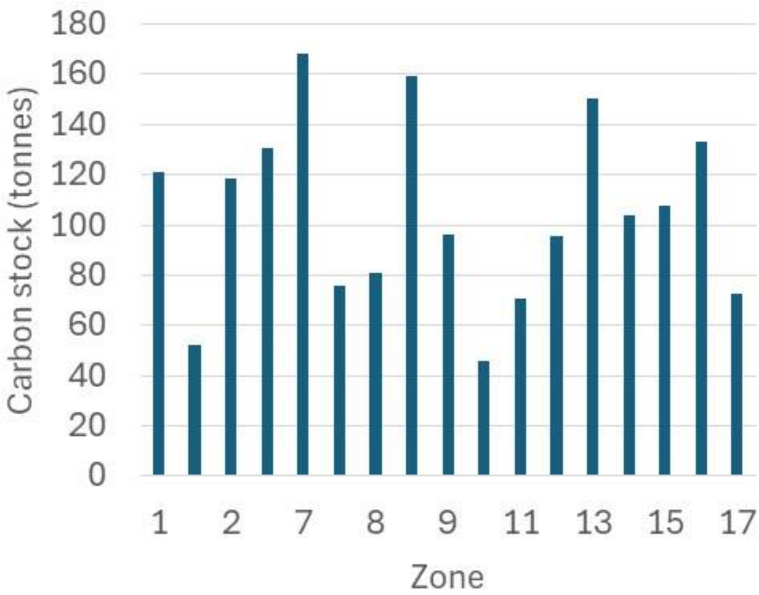


Figure 20 Standing stock of carbon for 3 km by 3 km square units of the Yorkshire coast. Zone 1 – North, Zone 17 – South.

5 Discussion

The primary aims of the Great Yorkshire Kelp Project have been achieved, namely to map and quantify the region's kelp forests particularly in terms of their function as blue carbon stores. A rich set of biodiversity associated with the kelp forest has been collected, and as a secondary goal, a description of the ecological and economic value of this will be provided in subsequent editions of the report.

It would not be possible to survey the entire coastal zone of Yorkshire within one year using high-resolution video imaging techniques. Hence, a modelling approach was taken and that brings with it certain caveats. These will be described in the following section in order to give an index of confidence in the carbon stocks provided.

5.1 Underwater survey techniques

Different methods of obtaining kelp extent and density were trialled during the initial surveys at Flamborough Head in May 2024. A piloted underwater vehicle with a camera was used with limited success, as the trailing cable connecting the vehicle to the operator created too much drag in the current and quickly became tangled in kelp. Use of remotely-operated underwater vehicles may better be used from fixed points from the shore during the low water slack water period. Alternatively, an ROV camera system could be towed behind the survey vessel using the ROV motors only to control height above the seabed (described in Raoult et al., 2025).

A second system with cameras fixed to vertical poles, or attached to weighted ropes, was more successful. The operator either viewed a live video feed on-screen on the research vessel to relay instructions to change the viewing height or maintained a constant depth above the kelp or the seabed by touching bottom with the weighted rope. The vessel was set to drift across the pre-planned survey corridor, usually from shallow to deep. Long transects of 500 m of high-quality seabed coverage could be captured with this method. However, losses of camera gear were high due snagging with boulders and wreckage along the drift track. Low-cost underwater video cameras (~£50) would be the choice for future surveys rather than more expensive Go-Pros. Adding more camera views would better restrain the estimate of kelp per unit area.

Quantification of underwater video was a time-consuming process and required an expert to score each segment, particularly for biodiversity. Automated video counting techniques are in use in other studies (for fish – Zheng et al., 2024), and the video collected here will no doubt make a valuable resource for training AI-based scoring.

5.2 Individual estimates of kelp carbon

The investment in underwater and shoreline sampling of the three main kelp species can be judged to be at the correct level. Our estimates of individual kelp fresh weight to dry weight ratios, and dry weight to carbon, were very similar to published estimates. Further sampling effort would therefore not have improved model accuracy.

5.3 Modelling kelp density from satellite imagery

Model accuracy will be further improved as more video transect data is ingested into the random forest model, and cross-comparisons with co-located Environment Agency surveys in 2024 are done. EA kelp estimates using another remote sensing technique – ship-based sonar – will potentially give wide-area estimate of the main sites (Runswick Bay, Cayton Bay and Selwicks Bay).

Improvement is needed to get a better representation of the mid- to high-density patches of kelp that are currently capped at 5 individuals m^{-2}, as well as avoiding any potential false positive results. The model has been trained on video transects to sites to the north of the study area (Staithes to Whitby, squares 1 to 5 and Cayton to Filey Brigg, squares 15 to 17 in Figure 17) and hence will have highest accuracy for the northern-to-mid section of the Yorkshire coast. Only one satellite image has been used in this report, selected from the freely-available Copernicus programme. There would be great benefit in using other medium to high-resolution multispectral satellite imagers from the commercial sector, from platforms such as WorldView, Planet, and Pleiades. Future investigations could also use autonomous unmanned aircraft (drones), perhaps launched from the clifftop at sites such as Ravenscar where the kelp beds are long, narrow and difficult to view in satellite images. A low-flying drone would be capable of mapping at a scale where individual kelps could be counted (subject to extreme low tides and clear water conditions). Airborne remote sensing is another possibility to produce very high-resolution images (<1 m pixel size), but with much longer flight paths than those achievable with drone surveys. Hyperspectral sensors of the CASI-type could allow discrimination of different algal types ((Simms, 2003).

The relatively shallow depth of the Yorkshire kelp forest also allows kelp extent mapping using citizen science approaches. For example, the authors have mapped a 1 km section of the Flamborough South Landing kelp forest using one observer on shore to GPS-locate the upper limit of the kelp forest, and another in a kayak equipped with a tracking GPS to paddle around the outer limit of the kelp. Given the increase in sea-kayaking and paddle-boarding on the Yorkshire coast, and the decline in SCUBA diving, these could form a strand of any future monitoring programme. A great deal of local knowledge as to kelp presence is held by the coastal fishing (and recreational angling) community, and this should not be overlooked.

5.4 Yorkshire kelp carbon stock

Our estimate here of ~2000 tonnes of kelp carbon as standing stock for the Yorkshire coast can be compared with the previous estimate for the whole English east coast of 58,400 tonnes (Burrows et al. 2021; 'B21'). Given that there are essentially no large kelp populations to the south of Flamborough Head, the comparison is between the area of the present study (Staithes to Flamborough, ~120 km[5]) and that of B21 from Berwick to Flamborough, that is ~375 km. The two estimates are far apart even after consideration of the different lengths of coastline (58,400 * 120/375 = 18,700 tonnes C). Our kelp carbon estimate is only 10% of the B21 one after scaling for coast length. The reason for the discrepancy lies in the different

[5] Based on the length of the English Coastal Footpath

modelling approaches. The present study used in-water video to verify kelp extents based on satellite imagery using machine learning, with the only constraint being that no kelp could be found deeper than 5 m. The B21 approach used a species distribution model that appears to overestimate kelp extent in areas of unsuitable substrate and water clarity, such as the Humber estuary. It is likely that the B21 model greatly overestimates both the horizontal distribution, and the offshore extent of kelp distribution into deeper waters[6]. An alternative argument would be that the kelp distribution has greatly contracted in recent years. Perhaps catastrophic storm events such as Storm Emma in March 2018, and Storm Arwen in November 2021 removed large areas of kelp? Remote sensing image sequences could help to estimate the amount of material stranded in 'wash-up' events following east coast storms.

A further check on annual carbon production can be done by using the UK mean carbon fixation rate of 340 gC m^{-2} yr^{-1} (Smale et al., 2020c) and applying that to an area of known kelp forest size. The largest (and probably densest) Yorkshire kelp forest is the bed in Zone 5 to the east of Whitby harbour. This bed has an area of 250,000 m^{-2} (25 ha), therefore the annual carbon uptake can be calculated as 250,000*340/1000/1000 = 85 tonnes. This primary production estimate includes material lost in organic form from the blades to the water and would be an over-estimate of actual carbon production (carbon fixed in blade, holdfast and stipe material). The estimate of annual blade production presented here for the whole of Zone 5 is very similar, at 76 tonnes carbon, which would agree well with the higher overall productivity value. Detailed study of kelp blade production rate would be required in order to further constrain these estimates. Whilst this can be done easily for kelps accessible at low tide on foot or by snorkelling, and such work is on-going at the University of Hull and Newcastle University, growth estimates of sub-tidal kelp would require SCUBA diving to tag and measure thalli over a period of months.

5.5 Limiting factors

Work in the 1970s showed that kelp forests extended to 9 m below low tide at sites along the Yorkshire coast (Sheppard et al., 1980). The present-day lower limit was not more than 4 m depth for individual kelps, with dense forest areas ending at 2 m to 3 m. This indicated a large change in vertical distribution over 50 years. The photophysiological and laboratory studies presented here showed that the three Yorkshire kelp species were functionally 'in good health', and this would be supported by observations of widespread recruitment of very small juvenile kelps at many sites in September 2024 (though not at Flamborough South Landing). Disease can be ruled out as a factor limiting kelp distribution – no obvious signs of necrosis or tissue decay were seen. Two main reasons are likely to be causative for the observed strong decrease in kelp density with increasing depth - either acting alone or together. These are irradiance (light) and grazing.

5.5.1 Irradiance

Kelp require a sufficient amount of light for photosynthesis and growth. Their cells are heavily-pigmented and photosynthetic measurements showed that the three species are light-saturated at a relatively low level of light, approximately 15% of full sunlight in mid-summer. Sunlight is reduced quickly with increasing depth in the water column, and the

[6] To achieve the carbon stock of B21 would require a kelp density of 800 gC m-2 with a kelp forest width of 200 m for the entire 120 km Yorkshire coast.

relative rates of decline of kelp and that of light are very similar. Both light and kelp density are reduced to about 1% of their surface value at a depth of 5 m below low tide[7]. Underwater transparency in the North Sea is known to have decreased over the 20th century (Capuzzo et al., 2015) and it is possible that this decline has continued into the 21st century. There are three factors controlling underwater light penetration: the amount of sediment in the water, the amount of dissolved organic material in the water (cDOM), and the concentration of phytoplankton. Phytoplankton levels are relatively low in Yorkshire coastal waters and insufficient to alter underwater light attenuation. In contrast, sediment loads and cDOM can be high but vary from site to site. Examination of the Environment Agency coastal water quality recordings since 2005 would reveal any trends relevant to kelp growth.

5.5.2 Grazing

It was evident from the first video surveys that the deeper zone below the present-day lower limit for Yorkshire kelp showed high numbers of the edible sea urchin (*Echinus esculentus*). Urchins are one of the main consumers of kelp material, alongside smaller organisms such as the blue-rayed limpet. Reduction of kelp forest lower limits by sea urchins, and the resulting 'urchin barrens' is a widespread global marine ecological phenomenon and has been observed in the UK and in Norway (Sivertsen, 2006). Quantification of sea urchin densities along the Yorkshire coast will be done during a subsequent biodiversity assessment of the video data.

Separation of irradiance and grazing as factors controlling kelp distribution could best be done using experimental techniques pioneered by earlier generations of kelp ecologists. Urchin removal, anti-gazing cages and kelp transplantations would form the set of experimental tools required for this type of research.

5.6 Future directions for Yorkshire kelp conservation

Kelp forest populations across the UK are generally considered stable and relatively free from direct anthropogenic pressures (Smale et al., 2016). Most kelp species in the UK that are found in any considerable densities occupy their central range, meaning they are also less exposed to environmental stressors such as extreme temperatures[8]. A recent survey of UK kelp experts found no evidence of widespread kelp losses, though two regions — Durham and Sussex — were identified as having experienced notable localised shifts in kelp forest structure (Wilding et al., 2023).

In Durham, historic coastal mining operations resulted in the deposition of millions of tonnes of sediment-based waste, smothering nearshore habitats and leading to widespread habitat loss, including kelp forests (Hydraulics Research Station, 1970; Hyslop et al., 1997). Anecdotal evidence suggests total loss of kelp in some areas that were heavily affected by mine waste disposal. Since the cessation of waste disposal in the late 20th century, extensive remediation efforts (e.g., *Turning the Tide*) have allowed significant recovery of the coastline to take place. Today, natural recolonisation of kelp has occurred, and the legacy

[7] based on an attenuation coefficient, K_d, of 0.9 m^{-1}.
[8] Notably, Alaria esculenta is a cold temperate species at its thermal range limit, and was not record in 2024 surveys.

impacts of historic disturbance on kelp forest ecosystems are now almost undetectable (Catherall, pers. comm., 2025).

In Sussex, kelp forests have declined by an estimated 95% since the 1980s (Mallinson, 2020), primarily due to damage from a large storm event and a subsequent increase in trawling pressure that inhibited natural recovery. In response, a trawling ban was introduced in 2021, and the Sussex Kelp Recovery Project is now monitoring signs of ecosystem recovery.

Elsewhere, in the northeast of England, particularly around the Farne Islands and St Abbs, localised urchin barrens have been observed (Moore, pers. comm., 2022). While these represent potential grazing pressure hotspots, healthy surrounding kelp populations suggest these impacts are currently localised and not affecting broader forest stability.

Despite the relative resilience of UK kelp forests, continued monitoring is essential to detect early warning signs of degradation and prevent future losses. The work conducted here suggests current canopy-forming kelp beds are limited to depths of approximately 2 m BCD. This is shallow compared to historical records from this area and findings from similar latitudes, where kelp forests have been documented at depths approaching 10m. This shallowing of kelp forest habitats may be driven by factors such as increased turbidity and increased grazing pressure as described above.

If these limitations were to be alleviated, a deepening of the kelp forest is biologically feasible — potentially having a vastly positive impact on habitat area. This expansion could result in a significant increase in carbon standing stock and sequestration potential, habitat availability, biodiversity support, coastal protection and the provision of ecosystem services such as tourism and improving fisheries. In a region like Yorkshire, where coastal erosion is a growing concern (Pye & Blott, 2022), the expansion of kelp forests could be a nature-based solution with multiple co-benefits.

Looking ahead, maintaining the health and resilience of Yorkshire's kelp forests will depend on proactive management. Efforts such as improving water quality, monitoring and managing grazer populations, and promoting suitable habitat conditions can help ensure these ecosystems thrive into the future. These actions may also create the conditions for natural expansion of kelp beds, enhancing their ecological and carbon storage potential. While current populations appear healthy and functional, establishing robust baseline datasets and maintaining ongoing monitoring will be essential to detect any emerging changes and guide timely, informed conservation responses. At present, there is no immediate need for active restoration, but efforts to broaden our understanding of the factors shaping kelp forest structure, as well as those limiting their depth extent, will be key to sustaining and potentially enhancing the benefits these habitats provide for future generations.

5.7 Summary of recommendations

5.7.1 Survey Methods & Equipment

Use low-cost underwater cameras (~£50) instead of expensive Go-Pros to reduce loss-related costs during drift surveys.

Add more camera angles/views to better estimate kelp per unit area during video surveys.

Explore alternative ROV setups: use fixed shore-based launch points during slack tide or tow a camera system using ROV motors for height control.

Consider autonomous drones launched from clifftops (e.g., at Ravenscar) for high-resolution mapping of narrow kelp beds during low tide and clear water conditions.

Investigate airborne remote sensing with <1 m resolution or use hyperspectral CASI-type sensors to distinguish algal types.

5.7.2 Data Processing & Modelling

Adopt AI-based video analysis for biodiversity scoring to reduce expert time demands (video from this project could support model training).

Continue training the random forest model with more video transect data to improve kelp density estimates.

Cross-validate satellite-based kelp models using Environment Agency sonar survey data from 2024.

Incorporate commercial satellite imagery (e.g., WorldView, Planet, Pleiades) alongside Copernicus data to improve model accuracy.

Improve detection of dense kelp patches currently underrepresented (capped at 5 individuals/m^{-2}), and work to reduce false positives.

5.7.3 Experimental Research

Conduct urchin removal and anti-grazing cage experiments to further understand the effects of grazing and light limitation on kelp depth distribution.

Measure kelp blade production rates through in situ tagging — intertidal areas by foot/snorkel; subtidal areas by SCUBA.

5.7.4 Citizen Science & Local Knowledge

Utilise citizen science approaches for shallow kelp mapping (e.g., GPS tracking from kayak + shore observer).

Engage local sea users (e.g., anglers, fishers, paddleboarders) to harness local knowledge for ongoing monitoring.

5.7.5 Environmental Monitoring

Review Environment Agency coastal water quality data (since 2005) to assess trends in turbidity and organic matter affecting underwater light conditions.

Quantify sea urchin densities along the coast as part of ongoing biodiversity video analysis.

5.7.6 Conservation Strategy

Consider at a later date the need for active kelp restoration in Yorkshire; current populations are healthy and functioning, but only present in a very narrow band extending to around 3 m BCD.

Prioritise proactive management: improve water quality, manage grazer populations, and promote conditions for natural kelp expansion.

Establish robust baseline datasets and continue long-term monitoring to detect emerging changes and guide responsive conservation efforts.

Advance understanding of ecological drivers: further investigate the factors influencing kelp forest structure and the limitations on depth extent to support future conservation planning and habitat enhancement.

5.7.7 Future Expansion Potential

If pressures preventing further kelp depth penetration were mitigated (i.e. light and grazing pressure), kelp forests may expand to deeper zones (e.g., up to 10 m BCD) — this could:

Increase carbon sequestration and storage capacity.

Increase habitat availability and boost biodiversity.

Potentially improve coastal protection through wave attenuation.

Support ecosystem services (e.g., fisheries, tourism).

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