A review of the current methods used to estimate the macroalgal standing stock in England and Wales

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Foreword

This report provides Natural England and Natural Resources Wales with a useful review and assessment of the tools and methods used to calculate macroalgal distribution and biomass around UK coasts, with particular emphasis on commercially important species such as large subtidal kelp (mostly Laminaria species) and knotted wrack (Ascophyllum nodosum). This is important because of the increase in commercial seaweed activities and interest along with the lack of standing stock baseline or standardisation of approach. The report can be used as a basis for discussions with interested parties.

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Executive summary

Background

Interest in gathering seaweed continues to increase around the UK with Natural England and Natural Resources Wales (NRW) increasingly being approached for advice regarding large scale collection, including commercially important species such as large subtidal kelp (i.e. mostly *Laminaria* species) and knotted wrack (i.e. *Ascophyllum nodosum*.

Currently, there is a lack of information concerning the distribution and quantity of macroalgal biomass around the UK with uncertainty in the best methods to quantify for different species. A review and refinement of the potential methods available to assess the distribution and to calculate kelp / *Ascophyllum nodosum* biomass, which are affordable, accurate and repeatable, would help understand the impact of the activity.

The aim of the project is to provide Natural England and Natural Resources Wales with a sound basis for discussions with commercial parties about how the assessment of standing stock should be carried out. The project objectives are to review and assess the existing data on methods to calculate macroalgal distribution and biomass, refining these for the species of interest to present suitable methods for assessing the distribution and calculation of biomass around the coast of England and Wales.

Red and green seaweeds are also targeted for harvesting and information about these and the application of methods has been noted by this project with species and information provided.

Review methodology

The project has reviewed a range of methods to assess distribution and biomass, these include direct survey methods (shore-based survey and dive survey), acoustic surveys and optical surveys using in-water sampling platforms (Autonomous Underwater Vehicles, Remotely Operated Vehicles and drop-down cameras) and aerial remote sensing (manned vehicles, unmanned aerial vehicles and satellites). Modelling approaches and key environmental variables used in these are also identified and discussed.

For each approach, information was collected on key characteristics including equipment and personnel required, spatial coverage, accuracy (to identify species, determine distribution, extent and biomass).

Costs have been reported where available but include estimates from a range of studies within the last six years. Multiple operational factors influence costs, such as the survey vessel and staff time required, the logistics of accessing the survey site and the amount of spatial and temporal replication required.

Results

For each approach, advantages and disadvantages are described. It is clear that between approaches there are trade-offs around accuracy of determining distribution, extent and biomass of macroalgae, the spatial coverage of the approach and costs. All approaches are subject to feasibility limitations including poor weather conditions, tidal state and suitability of habitats for the approach. For example, the use of drop down cameras, ROVs and AUVs will be physically restricted in intertidal and shallow water habitats, or where water depth is more are suitable (deeper, subtidal in more level terrain) currents, waves and weather conditions could limit safe vessel deployment and operation.

In shallow water with low turbidity, satellite imagery, aerial drones (unmanned aerial vehicles) or small planes can map extents and produce good images of intertidal and kelp habitats while covering wide areas. These survey options are limited to the shallowest habitats only with drones having limited payload and battery life. Satellite imagery and aerial photography are useful to assess the extent of intertidal brown algae and shallow kelp beds (depending on turbidity) but are unable to provide data of sufficient resolution on kelp biomass to support biomass estimations.

Remote sensing using photography by satellite, aircraft or drones is unsuitable to assess subtidal populations (deeper than 6 m) in turbid conditions but acoustic methods using sonar have shown promise for broadscale surveys.

At the smallest site-level scale, i.e. tens of metres, the most suitable approach for assessing species presence and extent would be to target key areas and undertake shore surveys and SCUBA diving surveys as these are the best method of providing accurate estimates of species present, abundance, condition and biomass. Only shore and dive surveys are suitable to identify and map understorey species including green and red species. However these approaches are limited in spatial coverage, with broadscale surveys at the regional scale requiring large amounts of time.

At the middle scale, i.e. sites to shores, acoustic techniques may have the potential to provide the required spatial coverage of a harvestable area at a sufficient resolution to determine the spatial distribution of kelp, identify canopy height and distinguish patchy and dense coverage (but not differentiate between kelp species). However, these approaches are limited in spatial coverage, with broadscale surveys at the regional scale requiring large amounts of time. At the regional scale, optimal methods would involve the use of aerial photography from piloted planes or high-resolution satellite imagery accompanied by appropriate ground truthing.

To overcome the limitations associated with single approaches, multiple nested approaches provide a powerful solution to estimating distribution and biomass at broader scales than the site level, via direct measurements scaled up to broader areas through remote sensing and habitat modelling. This approach has been used in Nova Scotia, Norway, Brittany, Scotland and Ireland, where harvestable biomass is estimated through survey approaches at different scales, coupled with modelling approaches ground truthed by direct surveys (shore based and diver).

Contents

Introduction

Interest in gathering seaweed continues to increase around the UK with Natural England and Natural Resources Wales (NRW) increasingly being approached for advice regarding large scale collection, including commercially important species such as large subtidal kelp and knotted wrack (*Ascophyllum nodosum* referred to throughout this report as A*scophyllum*).

Currently, there is a lack of information concerning the distribution and quantity of macroalgal biomass around the UK with uncertainty in the best methods to quantify for different species. A review and refinement of the potential methods available to assess the distribution and to calculate kelp / *Ascophyllum* biomass, which are affordable, accurate and repeatable, would help understand the impact of the activity.

For the statutory nature conservation bodies to be able to provide meaningful advice on any harvesting proposal, they require knowledge of the spatio-temporal distribution and quantity / biomass of the target species. Traditional approaches such as diving surveys provide high accuracy and resolution, however, they are time-consuming, expensive and limited to small areas. Remote sensing (e.g. using satellites, planes, drones, sonar) have been used in a number of countries, including the UK (Brodie and others, 2018) to estimate distribution / biomass of different algal species over large scales.

Current key issues / challenges:

- The methodologies for measuring / monitoring kelp are challenging; the habitat is often found in relatively inaccessible areas with turbid water, exposure to wave action and changing tidal levels.
- The various methods of calculating distribution / abundance (diving, distribution modelling, remote sensing, sonar etc.) all have various, and often significant challenges e.g. cost and technical knowledge associated with using them.
- There are a variety of methods to obtain figures of biomass from surveys that can be used to extrapolate and represent biomass over a larger region but these have not been ground truthed.
- Biomass varies temporally and spatially, even over relatively small scales due to patchy distribution and response to environmental gradients.
- Some methods work better to calculate biomass for some species compared to others, therefore a single approach may not be optimal for all species.
- Clarity on the optimal size of area / scale to be surveyed to ensure that estimates remain accurate but are not so detailed that they are too labour intensive (level of a beach, stretch of coast, region etc).

Project aims and objectives

The aim of the project is to provide Natural England and Natural Resources Wales with a sound basis for discussions with commercial parties about how the assessment of standing stock should be carried out. The project objectives are to review and assess the existing data on methods to calculate distribution and biomass, refining these for the species of interest – Kelp spp., and *Ascophyllum* to present suitable methods for assessing the distribution and calculation of biomass around the coast of England and Wales

The specific objectives were to:

- Review current methods for assessing distribution of the species of interest (e.g. shore survey, diving, remote sensing, modelling etc.)
- Review current methods for estimating biomass from field-based measurements and scaling these up to large areas for example at the scale of a stretch of coast, possibly within a Marine Protected Area.
- Assess which methods are relevant to English / Welsh waters and suitable for the species of interest and level of accuracy required.

Report structure

The report consists of this introduction section, brief methods (evidence review), an overview of environmental requirements for kelp and *Ascophyllum* and data sources available for these. Approaches to mapping macroalgal extent, distribution and biomass is provided and this is supported by additional technical information in Appendices 3-6. Finally approaches to estimating biomass are discussed with recommendations provided.

Methodology

Alongside *Ascophyllum*, a number of kelp species may be harvested in England and Wales. Targeted species and life history characteristics relevant to this project are shown below in Table 1. Red and green seaweed are also targeted for harvesting and information about these and the application of methods has been noted by this project with species and information provided in Appendix 1. Asterisks in Table 1 denote the key targeted species.

Kelp are found at sub-tidal depths in the photic zone anchored to stones, boulders and rocky substrate. In coastal waters, light penetration sufficient to support kelp growth is limited to around 15 m (below chart datum), although in clear Atlantic water they can grow down to 40 m. Kelp plants extend up to the lowest intertidal area, just above the low water mark and different species are better adapted to different wave exposure conditions (Hawkins and Harkin, 1985). The influence of different environmental and ecological factors for each species (where information is readily available) are provided in a later section of this report.

Table 1. Species that may be targeted for harvesting in the UK and their life history characteristics and habitat. Names of key targeted species are shown in bold text.

Species	Group	Seasonal biomass variation	Life history
Alaria esculenta Dabberlocks, Bladderlocks, Winged Kelp	Kelp	From June-July growth rates slow and continual erosion along the frond margins can reduce the sporophyte to a holdfast, stipe and short length of the blade, in which state the sporophyte overwinters. In extremely wave exposed conditions, especially in winter months, the blade may be reduced to just the midrib.	Perennial (4-7 years) (Birkett and others, 1998).
Ascophyllum nodosum Knotted wrack Eggwrack	Brown	Lowest growth rates in Nov and Dec maximum in spring/summer. Grows slowly and plants can live to be several decades old. Individual fronds can become up to 15 years old before breakage.	Perennial.
Laminaria digitate Oarweed	Kelp	Growth is rapid from February to July, slower in August to January, and occurs diffusely in the blade (Kain, 1979).	Perennial (4 to 6 years) (Birkett and others, 1998).
Laminaria hyperborean Forest Kelp, Northern Kelp, Tangle Weed, Cuvie, Cuvy, Redware	Kelp	Adults grow rapidly until about 5 years old. Peak growth occurs during winter and spring (November to May) and stops in summer initiated by a photoperiodic response to day length. The new blade grows below the older from November onwards. The old blade is shed in spring and early summer (Tyler-Walters, 2007).	Perennial (up to 20 years)
Saccharina latissima	Kelp	Juvenile sporophytes take eight months to reach an average size (1-2 m in length; Gerard and Du	Perennial (2-4 years).

Species	Group	Seasonal biomass variation	Life history
Sugar Kelp. (Previously Laminara saccharina)		Bois, 1988). Growth occurs from March to November although elongation of the frond only occurs between March and May due to high levels of abscission from July to November (Nielsen and others, 2014).	
Saccorhiza polyschides Furbelows, Furbelowed Hangers, Bulbous Rooted Tangle	Kelp	Fast growing, annual and opportunistic species. The large sporophytes (adult plant) are present on the shore from April until winter. In autumn they commence fruiting and start to decay, leaving behind the bulbous holdfast, which remains on the shore to overwinter or be washed off (Salland and Smale, 2021; White, 2008a). Sporophytes typically have a lifespan of less than 10 months. However, plants produced late in the season may overwinter and live for 14-16 months) (White, 2008a).	Annual
Himanthalia elongata Thongweed	Brown	Usually has a biennial lifecycle, reproducing once and then dying but may survive for up to 5 years (White, 2008b). Typically a small ‘button’ stage persists before rapidly-growing strap-like receptacles emerge in spring through to autumn.	Biennial

Desk based review of current methodologies

The evidence review adopted a Rapid Evidence Assessment approach for the evidence review in order to supplement in-house information from previous work carried out by the project team and provide an audit trail. The review included a range of information sources, focusing mainly on published scientific literature and grey literature.

The evidence review used a set of search terms (see Appendix 2). Initial searches were broad. Following review of the literature, further targeted searches were undertaken using Google Scholar and Google to address identified information gaps.

Searches of the grey literature (reports by statutory agencies etc) focused on using Google and targeted searches of organization websites. These included searches of JNCC monitoring resources.

The review also draws on work to estimate harvestable kelp biomass for Scotland (Burrows and others, 2018) and Ireland (Hession and others, 1998, Blight and others, 2011) and Brittany (Bajjouk and others, 2015).

Environment and species distribution

Environmental covariates that can be measured may be usefully incorporated into habitat suitability models and other mapping approaches to estimate the extent, distribution and biomass of *Ascophyllum* and kelps. Habitat requirements are species specific and are outlined briefly in Table 2 below. Key local environmental variables determining habitat suitability for macroalgae are depth (relating to light availability) and elevation (relating to desiccation/thermal stress), wave exposure and the presence of suitable substratum. All the species considered are usually found growing attached to hard substratum, but in some more sheltered areas may grow on boulders, cobbles and in very sheltered areas may be found as unattached forms. These factors are typically incorporated in models of species distribution (see Table 2). Other important factors influencing habitat suitability are light penetration (related to depth but also influenced by turbidity, aspect and coastal geomorphology), temperature, nutrient availability and salinity. Optimal growth is typically reported at salinity of 33–35 psu (full salinity) on the practical salinity scale (Kerrison and others, 2015). Suboptimal conditions such as very low nutrients or very high light, can lead to physiological stress, reductions in growth rate, increase in tissue degradation or even death (Kerrison and others, 2015). However, these factors and short-scale fluctuations in conditions such as temperature and local scale ecological interactions are less likely to be available to inform species distribution models.

Substratum

Substrates composed of rock and boulders are most suitable for *Ascophyllum* and kelps (Hession and others, 1998). Mobile sediments such as sand, mud and gravel do not provide stable attachment surfaces for holdfasts, although kelps may occur in sand these are typically sparse. Mixtures of boulders, cobbles and bedrock or mobile sediments such as sand will increase patchiness across shores due to the matrix of suitable and unsuitable habitats (Johnson, 2020). Disturbance from scouring may prevent survival of longer lived *Ascophyllum* and kelps and result in replacement by opportunistic species such as *S. polyschides* or *S. latissima* (Stamp and others, 2022).

Depth

Depth limits light penetration and will generally determine the lower limits of the kelp forest. The maximum depth limit of kelp forests around the UK is about 15 m (below chart datum) (Smith and others, 2022) but varies considerably between regions due to differences in turbidity related to sediment loading and resuspension, phytoplankton productivity, epiphytic growth, substrate availability and sea urchin grazing. The lower limits for individual species is shown in Table 2, with the lower limit for *Laminaria* species generally considered to be about 1 percent of surface irradiance (Birkett and others, 1998).

Temperature

Temperature is a key factor at a national and European scale influencing habitat suitability for macroalgae (Westmeijer and others, 2019). Temperature has a direct effect on the metabolic rate and ability to successfully reproduce. This creates specific temperature range envelopes within which they can successfully grow. Kelps are highly tolerant of the winter temperatures in Europe. *L. digitata* and *S. latissima* can tolerate temperatures of −1.5 °C, while *S. polyschides* has a lower limit of 0–1 °C (Tom Diek, 1993). High summer temperatures (such as those experienced during marine heatwaves) can cause mortality but are more likely to be of concern at the southern range edges of species more adapted to cold-waters (Filbee-Dexter and others, 2020; Straub and others, 2019).

The geographic distributions of large kelp species (e.g. *L. digitata*, *L. hyperborea*, and *S. latissima*) appear to be limited by summer and winter isotherms and some reviews have predicted declines in macroalgal abundance due to environmental change (Yesson and others, 2015). *A. esculenta*, for example, reaches its southern extent in Northern France and population distribution may respond to future climate change (Mieszkowska and others, 2006).

Yesson and others (2015) found that in a UK wide study, *L. digitata* and *L. hyperborea*, abundance was positively correlated with summer temperature and negatively correlated with winter temperature. However, the abundance of *L. digitata* has increased significantly in the northern North Sea, the region in the British Isles that has seen the largest temperature rises over the last 30 years. In contrast*,* *L. hyperborea* shows a significant decrease in abundance in the English Channel and a significant increase in abundance in the Irish Sea. These patterns may be underpinned by conditions required for reproduction and different life stages (Yesson and others, 2015). The abundance of *S. latissima* responded negatively to both summer and winter temperatures and *Himanthalia elongata* was negatively correlated with winter temperatures. For *Ascophyllum*, warmer summer and winter temperatures appear favourable (Yesson and others, 2015). Other studies have reported an increased abundance of *Laminaria ochroleuca* in southwest England, again in response to warming trends (Smale and others, 2015). However, long-term temporal trends in kelp distribution and abundance remain poorly understood, due to a lack of robust baselines and sustained monitoring.

Wave exposure

Wave exposure is a key habitat variable for *Ascophyllum* (prefers more sheltered shores in a range of studies from Scotland (Burrows and others, 2012) to the Iberian Peninsula (Martínez and others, 2012). Wave exposure is a key determinant of habitat suitability for kelps and also mediates competition between species (see Table 2).

Ecological factors influencing *Ascophyllum* and kelp

Other factors that influence macroalgal growth include changes in the abundance of grazers such as limpets that limit canopy growth (Davies and others, 2007) and may control the upper limits of species that can survive in the lower intertidal, including *H. elongata* (Southward and Southward, 1978). In the subtidal grazers such as *Echinus esculentus* may control the lower limits of kelp beds (Kain and others, 1966).

Competition between species, mediated by environmental conditions is also apparent. In less wave exposed areas, *Alaria esculenta* is outcompeted by *L. hyperborea* and *L. digitata* and *L. digitata* is outcompeted by *L. hyperborea* (Hill, 2008b). *S. polyschides* competes for space with *L. hyperborea* and the upper limit of *S. polyschides* is related to the lower limit of *L. hyperborea*. Where *L. hyperborea* is absent the species may extend up to the extreme low water springs mark (Hawkins and Harkin, 1985).

Table 2. Habitat preferences for key targeted species. Names of key targeted species are emboldened.

Species	Habitat
Alaria esculenta	Attached to rock and boulders, including mobile boulders. From low water into subtidal to 35m deep where light penetration allows. Dominates the sublittoral fringe in areas exposed to severe wave action or surge gullies where wave exposure or currents limit *L. hyperborea* and *L. digitata* (Birkett and others, 1998). Often appears early in the algal

Species	Habitat
	succession (c. 3 months after clearance of dominant algae) before being out-competed by other kelp species (in moderately wave exposed shores). See review by Stamp and Williams, 2021.
Ascophyllum nodosum	Attached to rocks and boulders on the middle shore in a range of habitats, from estuaries to relatively exposed coasts (Hill and White, 2008). As exposure to wave action increases the number of plants becomes progressively less and they consist increasingly of stumps and short lived shoots (Hill and White, 2008).
Laminaria digitata	Lower intertidal and sublittoral fringe, attached to hard substrata. Also occurs in deep rock pools up to mid-tide level. The lower depth limit for growth and survival is determined by water clarity, competition (with *L. hyperborea*) and grazers. In the Isle of Man the lower limit is at 1-2 m below the lowest astronomical tide and at Milford Haven it has been recorded at 5 m. The salinity optimum for *L*. digitata is full salinity. The greatest wet weight occurs at low wave exposure (mean significant wave height <0.4 m) decreasing by a mean of 83% in medium to high wave exposures (mean significant wave height >0.4 m; Gorman and others, 2013).
Laminaria hyperborea	Not found in areas influenced by sediment (e.g. sand) scour. Absent in areas of extreme wave action or currents (e.g. surge gullies) since the stiff stipe is likely to snap or holdfasts tear off. It is also absent from sheltered areas. From the extreme low water mark to depth, where it grows attached to hard substrata. Maximum depth is determined by light penetration, but can exceed 30 m depth in clear waters. Distribution models developed for Norwegian beds found that high kelp abundance is found mainly in relatively shallow and flat terrain in wave exposed and low current areas. (Bekkby and others, 2019). At international scales, winter temperatures are a key factor, empirically observed to drive distribution (Assis and others, 2016). Shifts in kelp population structure along depth gradients are strongly driven by light availability but mediated regionally by temperature (Smith and others, 2022). Tends to dominate subtidal reefs along wave-exposed open coastlines (Smale and Moore, 2017) and is the most spatially extensive kelp species in UK waters.
Saccharina latissima	Grows on hard substrata from lower shore into shallow sublittoral. Most abundant on sheltered shores and rarely grows in wave exposed conditions, due to competition from other kelp species and as it is vulnerable to dislodgement from wave action. Comparisons between biomass yields from two sites in Spain found significantly higher yields at

Species	Habitat
	a moderately exposed site compared with a sheltered site, with light exposure and water velocity cited as the determining factors of both populations health (Peteiro and Freire, 2013). The blades of *S. latissima* at the moderately exposed site were also found to have a large surface area than those at the sheltered site.
Saccorhiza polyschides	Normally attaches to rocks but is occasionally found loose-lying on small stones or shells. Colonizes abraded surfaces such as sand-scoured rocks or boulders that are mobile in winter and is characteristic of much disturbed substrata. It can form dense stands in sheltered areas and can tolerate strong currents (White, 2008a). From the low water mark to a depth of 35m. The available information suggests that it is stenohaline, as it does not naturally occur where salinity is below 33-35 psu (Norton and South, 1969).
Himanthalia elongata	Found attached to hard substrata on moderately exposed shores. It is found at the bottom of the shore, where it forms a band below *Fucus serratus* and above laminarians. Distribution appears to be controlled by the degree of wave exposure, presence of tidal currents and the availability of suitable substrata. The species grows best in areas with strong tidal currents and is most commonly found on semi-exposed shores where, it can be locally abundant. It is rarely found in exposed shores and occasionally forms dense stands on sheltered shores (White, 2008b).

Availability of environmental data to identify suitable habitats

Some of the variables influencing biomass may not be well-defined or the data may not be available an appropriate scale. The review has briefly identified information sources available to develop habitat distribution models at regional and national scales. (Table 3).

The ADMIRALTY Marine Data Portal (formerly UK Hydrographic Office) provides access to marine data sets held by the UK Hydrographic Office within the UK Exclusive Economic Zone (EEZ). This includes bathymetry among others.

Relevant information may be collected by the six regional programmes that form the National Network of Regional Coastal Monitoring Programmes of England. This network collects coastal monitoring data, including aerial and light detection and ranging (LiDAR) surveys, to inform shoreline management plans. Data, metadata, and survey reports are freely available to download.

The Channel Coastal Observatory (CCO) is an England-wide project to collect coastal monitoring data, including regular aerial surveys (from twice yearly to every few years, depending on the region) conducted at low tides (with a pixel resolution of either 0.1 × 0.1 m or 0.2 × 0.2 m).

Table 3. Environmental data to support development of species distribution modelling.

Environmental factor	Evidence available
Depth (bathymetry)	ADMIRALTY Marine Data Portal: Bathymetric surveys from various sources. EMODnet and Seazone LiDAR (National Network of Regional Coastal monitoring programmes) Swath (multibeam) bathymetry (National Network of Regional Coastal monitoring programmes)
Substratum	**ADMIRALTY charts** JNCC composite substrate product (vector - Folk 5 categories) BGS marine geoscience data collection (including multibeam backscatter and side-scan sonar data; seabed sediment particle size) Ortho-rectified aerial photography (National Network of Regional Coastal monitoring programmes)
Temperature	**Sea surface temperatures (SSTs) ‘Ocean Color Web’ portal (http://oceancolor.gsfc.nasa.gov/)**
Wave exposure	Wave buoys and tide gauges (National Network of Regional Coastal monitoring programmes) Wave fetch models based on coastal geomorphology (e.g. Burrows, 2012)
Topography	**LiDAR approaches available for some regions** Oceanwise Marine Themes Digital Elevation Model (DEM) (resolution of 1 and 6 arc seconds) (depth and slope)

Environmental factor	Evidence available
Currents	**National Oceanography Centre: British oceanographic Data Centre**
Species data	**Marine Recorder** **National Biodiversity Network (NBN)**

Review of approaches for mapping macroalgae

A range of approaches were identified for surveying macroalgae intertidally and subtidally to derive standing stock estimates. Table 4 identifies the approaches relevant to this study that were reviewed and whether these can assess the extent and distribution of macroalgal beds and biomass. Approaches are either direct (e.g. dive and shore survey) or indirect through the use of remote sensing methods (optical and acoustic). The project has focussed on the most commonly used approaches and not considered the use of small boat, i.e. kayaks for surveys or the use of Citizen Scientists to gather data. Neither were considered appropriate for this project which focusses on methods likely to be used by 1) harvesters or their contractors to assess habitat extent and biomass or were 2) appropriate for the development of broad-scale assessments.

The descriptions of approaches provided in Appendix 3-6 provide information on surveys (shore and diver), sensors (acoustic and optical) and different sampling platforms (vessel based operations and aerial/satellites). In some instances the sensor, e.g. a camera may be deployed by different platforms (e.g. drop down camera from vessel), autonomous underwater vehicle (AUV), remotely operated vehicle (ROV) and aircraft, drones (UAV) and satellites. Some sampling platforms may be able to deploy a range of sensors so that additional environmental data and spatial location data can also be gathered. These additional capabilities are briefly outlined in the relevant appendices.

Approaches for mapping the distribution and extent of harvested species varies between the intertidal and subtidal. Shore surveys, aerial surveys and drone surveys can be used for intertidal surveys with the use of satellites for mapping of intertidal macroalgae providing promising results (Brodie and others, 2018; Setyawidati and others, 2018, Murfitt and others, 2017). Kelps can be detected to a depth of 6 m (Uhl and others, 2016, study used satellite sensors), but this only covers a portion of their depth range. For subtidal habitats deeper than 6m below sea level, acoustic (sonar) techniques and drop down cameras are the most appropriate broader scale mapping approaches. ROVs can cover small areas and can be lifted and redeployed repeatedly over the same day (unlike diver surveys). AUVs are likely to be unable to operate in shallow subtidal habitats, particularly where the terrain is complex.

Remote sensing options do not replace the need for site observations to ground truth results (Davies and others, 2001). Approaches for ground truthing include the use of ROV or drop down camera to validate SONAR data (Blight and others, 2011), and field surveys to cross reference remote aerial sensing. Existing information from previous field surveys may be used to interpret aerial imagery but environmental changes and changes in vegetation cover after earlier field surveys, may compromise the image interpretation. Whenever possible it is recommended that field visits should coincide with the image capture.

Operation planning, logistics and data processing are a key part of any survey but are not reviewed for this report which focusses on capabilities.

Table 4. Approaches to macroalgal distribution, extent and biomass estimation reviewed by the project

Methodology	Species distribution and extent	Biomass estimation
Shore survey	Yes: intertidal species between MHWS and MLWS	Yes: destructive and non-destructive sampling
Dive survey	Yes: subtidal species	Yes: destructive and non-destructive sampling
SONAR (Single bean and Multibeam sound navigation and ranging)	Yes: Subtidal species	Estimated: based on length and density
Optical in water approaches: AUV/ROV and Drop down camera	Yes: subtidal species	Estimated: from still and video imagery
Aerial photography and other remote sensors (from aircraft and unmanned aerial vehicles (UAVs) two rotor and fixed wing (JNCC 2019)	Yes: intertidal and shallow subtidal species	Estimated: from imagery
Satellite imagery	Yes: intertidal and shallow subtidal species	Estimated: from imagery
LiDAR	Yes: intertidal and shallow subtidal species	Estimated: based on canopy height
Modelling approaches	Estimated: intertidal and subtidal species	Estimated: intertidal and subtidal species

Optical methods and spectral ranges

Aerial imagery has an established history for macroalgal mapping. In the 1950s, an estimate of Scotland’s kelp biomass was made using aerial photography and quadrat sampling across 8000 km^2 (Smale and others, 2013). Images of the coastline taken from aeroplanes, drones, or satellites can provide an overview of coastal habitats suitable for broad-scale habitat assessments and monitoring (Brodie and others, 2018). Optical methods can utilise standard photographic images taken by visible light cameras. Within the technical literature these are referred to as RGB because of the three bands of data representing the intensities of red, green, and blue wavelengths of each pixel.

Cameras can also capture additional spectral bands (i.e., not only red-green-blue) to provide further opportunities to identify unique spectral signatures among vegetation types. Sensors recording many bands are termed multispectral. In general, more bands offer a greater potential for reliably distinguishing between features. The two main types are multispectral and hyperspectral. These are referenced in the relevant approach appendices (Appendix 4 UAVs, Appendix 5 aircraft and Appendix 6 satellites) and are relevant for all platforms that can carry these sensors. Multispectral data provides the facility to use band combinations other than the simple red/green/blue combination of a visible light aerial photograph to highlight vegetation features. Macroalgae have high photosynthetic pigment diversity, the basis of the classification into three phyla—Ochrophyta (brown algae), Chlorophyta (green algae), and Rhodophyta (red algae)—with each showing unique pigment profiles. The difference in pigmentation enables separation of major groups of species but not necessarily between species in the same group by multispectral imaging. For example, green and brown species are more readily differentiated from each other, than two species of brown macroalgae. A difficulty in analysing aquatic plants is that the associated reflected light spectra vary by species and may overlap between members of the same family or vary due to condition (Uhl and others, 2013; Diruit and others, 2022, Bell and others, 2015). Wet and dry plants of the same species may also have different spectral signatures.

Water dampens the spectral signal, so the approach is not suitable for mapping deeper kelp beds, particularly in more turbid temperate waters (water clarity is generally better in the tropics). Timing of aerial remote sensing for the most favourable tidal state is essential for planning surveys and, of course, this control over timings is not possible for satellite images.

Image classification requires detailed knowledge of computer hardware and software, and surveys may generate high volumes of still and video imagery to analyse. Smale and others (2012), recorded the following image collection rates: divers 400 images/day, drop cameras 700 images/day and an AUV 15,000 images/day.

Some satellite and aerial imagery data is freely available and the resolution of this varies (Brodie and others, 2018). Figure 1 below shows a freely available infrared aerial image from the Channel Coastal Observatory. The scattered patches of kelp on the foreshore and the shallow subtidal are clearly identified in bright red, whereas the human made structures and rocky areas are grey and the areas of seawater are dark blue.

Figure 1. Freely available infrared image of shoreline outside the Marine Biological Association from Channel Coast Observatory. The image captures washed up macroalgae and strandline as well as intertidal live beds. Kelp beds are known to be present in the deeper area, but the full extent is not captured.

Spatial coverage and resolution

Spatial coverage and resolution for different types of method are identified below. Resolution refers to the smallest physical size/area of ground that can be differentiated. Further details are provided in the Appendices 3-6.

Table 5. Spatial coverage and resolution of different approaches.

Approach	Spatial coverage	Spatial resolution
Shore survey	Dependent on approach: examples 100m (transect)/per low tide (biomass) 0.08 km^2/hr (survey)	High (1cm)
Dive survey	Varies by size of dive team, approach, depth and local conditions 10 replicate 1 x 1 m quadrats per dive 0.0001 km^2/hr (survey)	High (1cm)

Approach	Spatial coverage	Spatial resolution
ROVs	<25m^2 to <1km^2	Imagery: High (1cm)
AUVs	>25m^2 <1km^2	High (1cm)
Drop down camera	2km^2/day	High (1cm)
SONAR	1-8km^2/hr	High (1cm)
UAVs	0.25km^2 - 5km^2	High (1cm)
Aircraft	40 x 40km	Varies according to equipment (0.1-0.3 m^2)
Satellite	Regional	Varies by satellite 30m- to 0.1 m^2 pixels.

Influence of environmental conditions

Prevailing weather conditions and tidal state will affect any monitoring study. Weather conditions should be considered, with surveys planned for times of the year that are likely to be less stormy. As well as preventing missions, storms with high-levels of rainfall will also reduce visibility in estuaries and near-shore environments as increased sediments are washed into rivers and wave induced sediment re-suspension increases.

Sites open to the prevailing wind and swell will require calm conditions for effective field survey. Tidal state will determine when shore surveys can take place and will influence the most favourable times for dive surveys. Aerial surveys will need to be planned around low water to map the intertidal and shallow subtidal.

In UK waters, visibility is generally reduced in spring and autumn as a result of phytoplankton blooms. As a general rule, summer may be the best time for operations and slack water and neap tides (to limit resuspension) the best time of day for optical methods. In nearshore areas with high tidal currents, this may mean a survey window of only an hour or so.

Macroalgal abundance and biomass will vary seasonally, with biomass typically lower over the winter than the summer, due to loss of annual species and loss and erosion of blades of perennial species by storms. Monitoring and survey planning should take into consideration this variability.

Table 6. Environmental factors affecting application.

Approach	Environmental factors affecting application
Shore survey	Weather conditions, tides, wave exposure, accessibility
Dive survey	Weather conditions, tides, wave exposure, currents, turbidity
ROVs	Weather conditions, wave exposure, currents, turbidity
AUVs	Weather conditions, wave exposure, currents, turbidity
Drop down camera	Weather conditions, wave exposure, currents, turbidity
SONAR	Weather conditions, wave exposure, currents
UAVs	Weather conditions, tidal state
Aircraft	Weather conditions, tidal state
Satellite	Cloud cover, tidal state

Accuracy of determining extent distribution and discriminating between species.

The accuracy of each survey method is reviewed in Appendices 3-6. The approaches reviewed vary in terms of accuracy of identifying species and trade-offs around spatial coverage and cost.

The most accurate approaches for surveying macroalgae are shore and dive surveys, with destructive sampling for biomass. These approaches can also assess other brown, red and green macroalgae present under *Ascophyllum* and kelp canopies as well as understorey juveniles.

Drop down cameras, ROVs and AUVs capture still and video imagery at high resolution (depending on turbidity) and are therefore useful to survey subtidal kelps.

Remote sensing using aerial photography, satellites and UAVs vary in spatial resolution and application. Remote sensing methods are unable to accurately map green, red and brown seaweed below canopies of kelp and *Ascophyllum*. UAV surveys for example underestimated the presence of understorey seaweed as these were often obscured by canopy forming species (Murfitt and others, 2017).

Sidescan sonar is one promising technique for differentiating species (Dijkstra and others, 2017) and can distinguish between canopy forming and filamentous seaweeds (Lubsch and others 2020). Automated sensing of macrophyte beds by AUVs also shows promise.

All of the remote sensing approaches have been shown to have some success in discriminating intertidal habitats and between groups of seaweed. However, identification to species level and discrimination of mixed beds is typically less accurate and such approaches cannot identify understorey species, including commercially important red seaweeds. Acoustic surveys for example can detect and map kelp canopies but in studies could not distinguish between the two principal species of kelp, *L. hyperborea* and *L. digitata* (Blight and others, 2011

Indicative costs

Where possible, indicative costs are provided in Appendices 3-6. Direct surveys are resource intensive for the small areas sampled and involve staff costs and ancillary costs (for example boats). However, remote sensing campaigns can be expensive with general costs challenging to estimate because of the variable costs of hardware purchase or hire (e.g. Boats, ROVs, UAVs) experienced staff time to operate the sensors and the costs of data processing and image analysis. However, such approaches may be cost-effective because of the spatial coverage.

Developing methodologies to estimate biomass

The most commonly used approaches for evaluating macroalgal biomass are direct sampling using shore surveys and quadrats and destructive sampling, where parts of the plant are removed and weighed. Other direct methods include non-destructive sampling using attributes such as plant length. Less reliable and less tested are indirect estimates of biomass using optical or acoustic methods.

Once biomass estimates are obtained they can be scaled up to estimate biomass over larger areas. Biomass estimates may be paired with habitat modelling approaches to define the extent of suitable habitat.

Direct methods of estimating biomass

A number of studies were identified that report direct biomass for *Ascophyllum* and kelp. A number of these are described below as the estimates of biomass were used with species distribution models to scale up biomass estimates for wider areas. In general, the literature on biomass estimates for *Ascophyllum* and kelp for England and Wales appears to be relatively sparse. Most studies are small-scale and site specific and/or outside the area of interest. A range of biomass estimates, such as wet and dry weights have been reported which restricts meaningful comparison between studies.

Quadrat-scale biomass of seaweeds can also be variable. For example, the average coefficient of variation for the dry weight m^{-2} of *Ascophyllum* surveyed on five shores in Brittany was 67% (Golley and others, 2011). This variability reduces certainty in scaled-up estimates of biomass. Confidence intervals for the total biomass of A*scopyllum* were typically 50% of the estimate (Cullinane, 1984).

Examples of previous projects to assess harvestable biomass include a study in Western Ireland for *Ascophyllum* (Hession and others, 1998). Site abundance estimates were made by mapping the area covered by *Ascophyllum* (using a GPS system) and then abundance was estimated (based on expert opinion) to give a harvestable quantity for the site. Estimates were ground truthed using dive surveys (of abundance over $20m^2$ for three sites). An echo-sounder was also tested against spot diving checks for its ability to identify and record the presence of kelp. Estimates produced by this methodology were considered to give a good indication of harvestable quantities.

Assessing biomass from plant attributes

Where plant attributes, such as length are correlated with biomass, biomass estimates can be derived. The Outer Hebrides study of *Ascophyllum* harvestable resource found that biomass (Wet weight per quadrat) was loosely correlated with average plant length. Longer plants are associated with greater yields (Burrows and others, 2012).

Blight and others (2011) found that biomass of *L. hyperborea* is directly correlated to stipe length and this was used as the basis for biomass estimates where canopy length is determined by sonar (Single beam echo sounder, see Appendix 5).

Indirect estimates of biomass

At present, there are few studies on the application of remote sensing, using visible light or multispectral imagery to the biomass assessment of macroalgae collected via UAV (Chen and others, 2022) or satellites (Pratama and Albasri, 2021). If reliable and validated, optical two-dimensional estimates of surface area distribution could be used to estimate standing stock biomass for a given macroalgal bed by multiplying extent by biomass per unit area as described below. However, identification to species level is challenging and will reduce the accuracy of results.

Scaling up biomass estimates

Where observations are limited, species distribution models offer a method to extrapolate direct observations on a small scale to apply over broad scales (Young and others, 2015, Westmeijer, and others, 2019). Examples of models can include those that are very simple and based on a single habitat parameter, to more complex models based on a range of mixed environmental covariates that have been analysed to have a direct effect on extent, distribution or biomass. A variety of statistical modelling approaches have been trialled, including regression models and Bayesian Belief Networks.

The development of models is a specialist subject with a vast literature and it is beyond the scope of this review to provide an introduction or overview although two key points should be noted. Habitat models are improved by samples across a range of variables and with training data from areas where the species is not found, as well as where it is likely to be abundant (Burrows and others, 2012).

The review identified a number of biomass models developed to ascertain the standing stock (harvestable biomass) of kelps and *Ascophyllum* and these are described below. Factors that determine habitat suitability for the targeted species are described above in the section on environmental and ecological covariates. These are likely to inform the development of predictive models for extent, distribution and biomass.

The steps to build predictive models are described by Van Son, and others (2020) and are generally applicable, although that study is based on *L. hyperborea* biomass estimation for Norway. The statistical model needs to include covariates that have a direct effect on the kelp biomass and field observations and must be based on a sampling strategy that is able to cover environmental covariates across gradients (including unsuitable habitat). Then species distribution models can be developed to estimate the spatial distribution of biomass and subsequently the biomass (standing stock within a given area).

Two studies from France developed statistical models of the biomass of *Laminaria* species and subsequently predicted the species' distribution of biomass in the Bay of Morlaix and the Molène Archipelago in Brittany, respectively, to estimate the standing stock. (Gorman and others, 2012; Bajjouk and others, 2015).

A model for the Outer Hebrides was developed to assess the *Ascophyllum* resource (Burrows and others, 2012). The model was based on measured biomass as average weight of *Ascophyllum* per quadrat, this was found to vary among the different lochs and regions in the study area and to be influenced by environmental variables (Burrows and others, 2012).

A two-stage regression technique was used to build a statistical model that firstly related *Ascophyllum* presence, and then plant weight and length to wave fetch and shore level. This was designed to allow for local or loch-scale variation in responses to similar environmental conditions if such variation were detected. The first stage model predicts the likelihood of presence of and used maps of a pre-existing index of wave exposure

(Burrows and others 2008). The second model predicts the size and weight of plants in areas where the species was likely to be found. Where relationships with environmental variables and among regions were statistically significant, these relationships were combined with the maps of wave fetch to produce estimates of *Ascophyllum* likely presence, plant size and weight at 200m intervals along the coastline. To estimate the total biomass in a surveyed area, the area of the intertidal zone (from onsite observations of the width of the intertidal) and the *Ascophyllum* zone, was multiplied by the length of the rocky shoreline in the area. The predictive model gave the biomass in kg as a product of the estimated area covered by *Ascophyllum* and the predicted average weight per unit area of rocky habitat in the locality.

Scottish maps of kelp biomass (*L. hyperborea*, *L. digitate*, *S. latissima* and *S. polyschides*) have also been created by refining and applying predictive habitat suitability models from previous estimations of kelp biomass around Scotland (Burrows and others, 2018 and references therein). Data on kelp abundance and their environmental predictors were collated from known sources but were replaced by survey data collected during the project to estimate biomass per unit area. The Scottish modelled predictions of kelp biomass show that while the general patterns of abundance are captured, the accuracy of estimates was compromised by the insufficient resolution of underlying seabed data.

Discussion

Review of approaches

The review has identified a range of approaches for mapping macroalgae (*Ascophyllum* and kelp) to support estimates of standing stock. A number of trade-offs between approaches are apparent based on coverage, accuracy and cost (of identifying species and determining extents). The review has also considered whether the approaches are applicable for other groups of macroalgae (red, green and brown) and this is considered for each method (see Annexes 3-6). A summary decision tree to support method selection is provided below (Figure 2, redrawn from Bennion and others, 2015, with permission). For most requirements, there is a trade-off between spatial coverage, resolution and resources (either field or desk based) (Bennion and others, 2015). Methods may be used in combination to overcome limitations inherent in each single approach. For example, direct sampling will be required to ground truth (validate) imagery and to support biomass estimations.

For site-based estimations of biomass carried out by harvesters, shore-based surveys for *Ascophyllum*, other intertidal seaweeds and sublittoral fringe kelps exposed at the lowest tides are the most likely technique to be adopted. Shore-based surveys require little equipment and surveys can be undertaken with relatively little expertise (beyond basic identification). The degree to which dive

surveys are recommended for deeper subtidal kelps is unclear and may depend on agency protocols around dive survey recommendations, based on the risk to divers of carrying out these surveys. Both shore and dive surveys for kelp can be replicated using fixed sampling points and species abundance and biomass counts can be supplemented by still or video imagery that will allow changes over time to be monitored.

Shore-based and dive surveys provide the most detailed surveys to determine the species present, extent, abundance (at the quadrat or transect scale) and biomass (via destructive or non-destructive sampling). They can be used to sample *Ascophyllum* and kelps. They can also be applied to other seaweed species that may be proposed for harvesting, although multi-species surveys are likely to increase the time required and therefore costs. These approaches provide the most accurate method of assessing standing stock and scaling up at the site level, using accurately mapped extents of macroalgal beds. However, the drawback of both approaches, is that spatial coverage is small, with dive surveys proving expensive. As such, this approach is not, neither are cost-effective or practical for broader scale assessments.

Satellite or airborne sensors cover large areas, but are limited by low resolution, the depth of penetration of visible and infrared wavelengths and cannot operate effectively in turbid temperate waters (Tait and others, 2019). Even where conditions are suitable for detecting kelp underwater, radiation reflected from the canopy is unlikely to provide information on kelp density or biomass as species can be difficult to separate and canopies can be mixed. The density of the canopy is difficult to accurately estimate from remote data. Manned flights provide a much larger geographic coverage and typically have high spectral resolution and range and moderate spatial coverage (Bolch and others, 2021) but are expensive in terms of hiring pilots and aircraft. Remote sensing by UAVs sits between this range of capability, providing imagery with a geographic footprint smaller than manned flights but larger than the single points provided by field survey. UAV-mounted sensors offer much higher spatial resolution than aircraft mounted imaging spectrometers but have lower spectral quality, smaller spectral range and a smaller spatial coverage due to lens specifications and UAV flight restrictions.

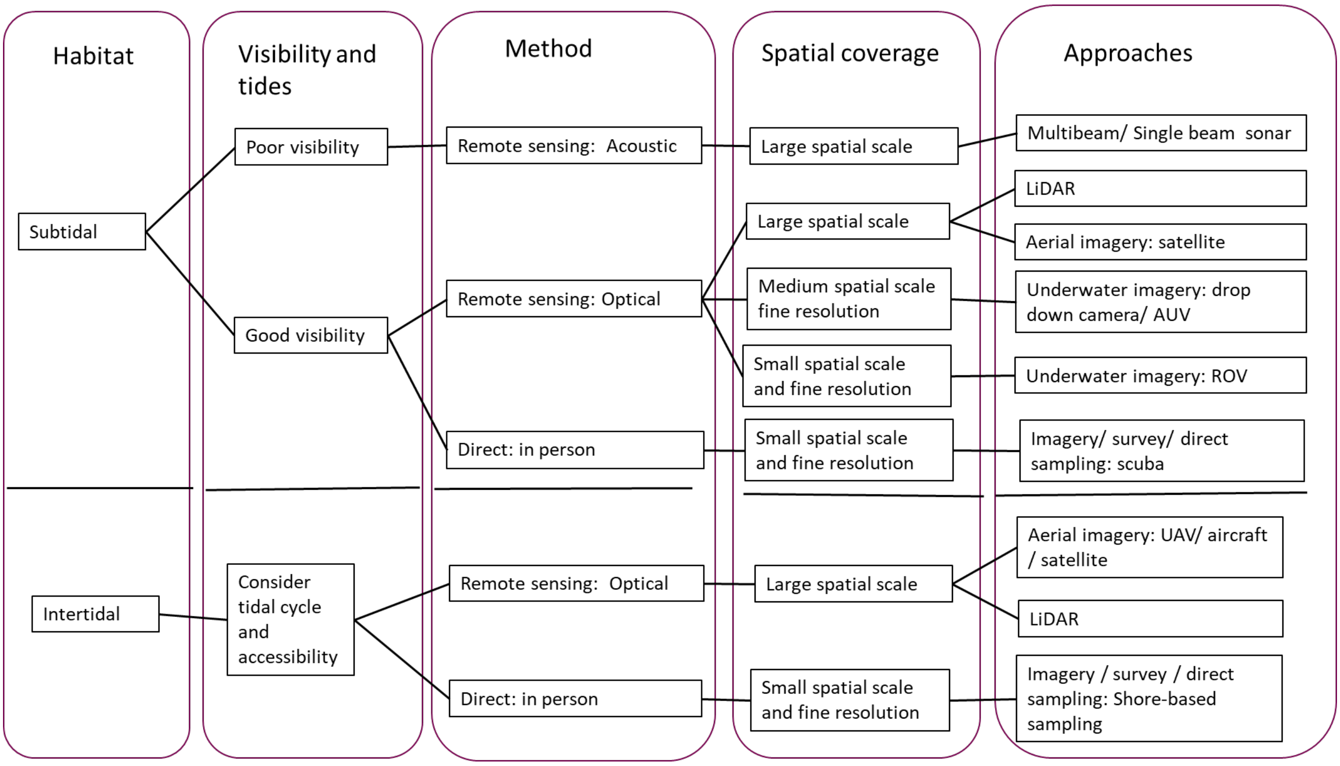

Figure 2. Summary of optical, acoustic and direct approaches to surveying (re-drawn from Bennion and others, 2015, with permission).

Available biomass information

The project sought to identify quadrat scale estimates of biomass of the relevant species for England and Wales. The review identified a number of studies that assess distribution and biomass of *Ascophyllum* and kelp species and the environmental variables that influence these. Relatively few biomass estimates were sourced and comparison between studies is compromised by variation in metrics used, for example, wet weight vs dry weight. There is additional variability between studies as different methods may be used to scale estimates, for example some studies use a full quadrat while others sample a few plants within a quadrat. In some instances, only the stipe is weighed, while other studies weight holdfasts and stipes. In addition, studies are typically small scale and therefore cover limited areas. There is little confidence in upscaling from these estimates as the relationship between abundance/biomass and the influence of environmental variables varies regionally (Smith and others, 2022).

While regional assessments have been developed for parts of Ireland and Scotland (Burrows and others, 2012) and habitat models have been developed, these should not be applied without sampling from England and Wales to provide direct biomass values to parameterise estimations.

Scaling up biomass estimates

Approaches have been trialled to estimate harvestable seaweed resources at broader scales using species distribution models coupled with environmental variables to predict species distribution, extent and biomass. Direct estimates of biomass can be combined with broader scale survey methods and modelling to bridge the information gaps in seaweed distribution at a range of scales, from high-uncertainty, large-scale estimation using remote sensing and models, through medium-uncertainty measurement using acoustic techniques, through low-uncertainty video and diving assessments giving confirmation of species identities and measurements of the size and abundance of macroalgae (Burrows and others, 2018).

There are limitations with what can be achieved by models (i.e. models provide a ‘likelihood of occurrence’, confidence in predictions is a limiting factor), for example, studies in the same region have shown conflict in the factors most influencing kelp distributions (Meleder and others, 2010; Gorman and others, 2013) and these differences would affect the accuracy of predictions. However, stratified sampling, adequate number of samples and sampling across gradients can improve the confidence in predictions.

Recommendations

At the smallest site-level scale, i.e., tens of metres, the most suitable approach for assessing species presence and extent to support biomass estimates would be to target key areas suitable for seaweed and undertake shore surveys and/or SCUBA diving dive surveys as these are the best method of providing accurate estimates of species present, abundance, condition and biomass. Only shore and dive surveys are suitable to identify and map understorey species including green and red species. However, these approaches are limited in spatial coverage and if required at a regional scale requiring large amounts of time and resource would become time consuming (and hence expensive) and may be unfeasible.

At the middle scale, acoustic techniques may have the potential to provide the required spatial coverage of a harvestable area at a sufficient resolution to determine the spatial distribution of kelp, identify canopy height and distinguish patchy and dense coverage (but not differentiate kelp species). For regional scale assessments, optimal methods may involve the use of aerial photography from piloted planes or high resolution satellite imagery accompanied by appropriate ground truthing. However, the expertise and time required for image analysis should be considered, although imagery may be freely available.

To overcome the limitations associated with single approaches, multiple nested approaches provide a powerful solution to estimating distribution and biomass at broader scales than the site level via direct measurements scaled up to broader areas through remote sensing and habitat modelling. This approach has been used in Nova Scotia, Norway, Brittany, Scotland and Ireland, where harvestable biomass is estimated through survey approaches at different scales, coupled with modelling approaches to predict biomass, ground truthed by direct surveys (shore based and diver).

Monitoring and survey data from both harvested and reference sites could be stored in a central repository and made publicly available, either voluntarily or as a licence condition. Accessibility of such data would begin to address gaps in knowledge concerning biomass and biomass variation at local scales to improve assessments.

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Appendix 1 Harvested green and red seaweeds (Note, some cells have been left blank)

Species harvested	Group	Seasonal biomass variation	Life history	Habitat
Chondrus crispus Irish moss, Carrageen	Red algae	Little seasonal growth	Perennial	Mid to lower rocky shore and in tide pools
Fucus serratus Serrated wrack, Toothed wrack, Saw wrack	Brown algae	Growth rate ranges from 4-12 cm per annum	Perennial	Low shore in sheltered to moderately exposed areas of coastline
Fucus vesiculosus Bladder wrack	Brown algae		Perennial	Low to mid shore in sheltered areas
Himanthalia elongate Sea spaghetti	Brown algae	Small growth	Bi-annual	Found attached to hard substrata on the lower shore, forms a band below *Fucus serratus* and above the kelps
Mastocarpus stellatus Carragheen, False Irish moss, Grape pip weed,	Red algae		Perennial	Attached to bedrock on the mid to lower shore often co-existing with *C. crispus*
Osmundea pinnatifida Pepper dulse				

Species harvested	Group	Seasonal biomass variation	Life history	Habitat
Palmaria palmate Dulse	Red algae		Perennial	Mid to lower shore, in pools and into the subtidal depths of 20m
Porphyra spp Laver, Purple laver	Red algae	In Wales growth is highly seasonal	Annual	Occurs singly or in dense mats throughout intertidal but mostly at upper levels
Ulva spp Sea lettuce, Green laver	Green algae		Annual	All levels of the shore

Appendix 2 Search terms

Search term	Hits	Search engine
Ascophyllum survey	7,560	Google Scholar
Ascophyllum biomass quadrat	1,070	Google Scholar
Kelp survey	55,900	Google Scholar
Dive survey kelp	19,000	Google Scholar
Remote sensing seaweed	23,800	Google Scholar
Satellite seaweed biomass	10,100	Plym Uni library-Primo
calculating biomass LiDAR macroalgae OR seaweed	13,500	Google Scholar
macroalgae biomass estimate	58,000	Google Scholar
Satellite imagery, Ascophyllum nodosum	17,100	Google Scholar
UAVs for coastal surveying of kelp	3650	Google Scholar
Seaweed biomass quadrat surveys	7,190	Google Scholar
UAV kelp	729	Google Scholar
seaweed estimate biomass image	20,400	Google Scholar
species distribution model Ascophyllum	12,000	Google Scholar
species distribution model laminaria	25,100	Google Scholar
species distribution model himanthalia	1,680	Google Scholar

Appendix 3 Shore survey

Description

The most common surveying method used for intertidal seaweed is *in situ* quadrat sampling surveys. Shore based survey designs can be adapted to the requirements and shore type, conditions and the species. Shore surveys can range in effort from walk over surveys to identify species present and the extent and distribution of seaweed beds to more detailed quadrat and transect survey that enumerate numbers of species present abundance and coverage and biomass (via destructive and non-destructive sampling).

Photographic records can be made to monitor changes in distribution and extent and cover distinguishing between areas of barnacles/mussels and seaweed cover. Percent cover of all species occurring within these assemblages can be estimated by using a point contact grid, either in the field or from photo analysis post fieldwork.

Gradients in biomass can introduce unintentional bias. Stratified sampling and/or sampling on a transect perpendicular to the elevational contours, improve subsequent abundance and biomass random quadrat placements.

Survey types can include:

- Walkover surveys to estimate coverage and extent, can be coupled with handheld GPS and data loggers.
- Line and belt transects to estimate cover of macroalgae,
- Quadrat surveys to estimate:
    - Percent cover
    - Actual counts
    - Abundance

Biomass can be measured using destructive sampling in-situ (cutting and weighing), or by bagging and removing individuals for later weighing, or a combination. For example, where biomass is high *Ascophyllum* and kelps, can be weighed on shore, while smaller red and green species can be bagged for later weighing.

Relocation of fixed sites through GPS supplemented by photographs and/or diagrams of characteristic topographical features should be used to relocate sites and repeat surveys over time for monitoring.

Equipment required

Quadrat (typically $0.25m^2$ or $0.5m^2$), spring balance (better than digital), transect line, levelling device to determine height of shore, GPS, to locate quadrats, Smartphone (location), camera and/or video.

Personnel. Minimum, at least one person with training to identify species and conduct survey, one note taker/ assistant and one bagger/weigher (for biomass estimates) is suggested.

Distribution mapping

Distribution of macroalgae can be mapped in the survey area, typically over a transect or belt line. Canopy forming species can be surveyed more readily than understorey algae or epiphytes.

Biomass estimation

While non-destructive sampling is possible, based on abundance and frond length, this is less accurate and not recommended instead of destructive sampling.

Costs

Dependent on personnel costs: £500-£1,250 for two staff. Most equipment required is relatively cheap and could be supplied by subcontractors.

Spatial coverage

The amount of shore that can be covered during a single low tide by a pair of surveyors will vary depending on a number of factors (Davies and others, 2001). These include the quantity of information required as well as the complexity and accessibility of the coastline.

Wyn and others (2000), discuss survey speeds on different shore types and quote an average speed of 0.08km^2/hr for shore survey. M. Burrows (report author) suggests that for biomass estimation a 100m transect/per low tide can be completed.

Accuracy: Species identification

High accuracy for trained surveyors.

Accuracy: differentiate kelps

High accuracy for trained surveyors.

Accuracy: species density/condition

High, for trained surveyors.

Accuracy: species extent

High, for trained surveyors but extent information will depend on survey design, belt transects and random quadrats will not delimit species extent.

Influence of environmental variables

Weather conditions are key and periods of high winds and heavy rain will limit surveys.

Advantages

High accuracy of survey, species identification and abundance and biomass estimates within survey footprint.

Disadvantages

- Rocky substrata may be challenging to access due to weather and currents (it is assumed that harvesting is carried out on shores with access).
- Time consuming
- Spatial scale relatively restricted

Examples of studies and methodologies

A number of projects have estimated the harvestable biomass of *Ascophyllum* using shore-based surveys to assess the distribution and extent of beds and to scale up quadrat level biomass measurements to estimate the total stock of *Ascophyllum* for harvest. Studies and methods are outlined below.

In the Outer Hebrides (Scotland), Scottish Enterprise and Highlands and Islands Enterprise commissioned a project to assess the *Ascophyllum* resources of the Outer Hebrides. Surveys, described by Burrows and others (2012) aimed to assess the size and density (kg/m^2) of *Ascophyllum*. Sites that were likely to provide suitable habitat (based on rock substratum and wave fetch –sheltered) were pre-selected. The survey method allowed 2 to 3 site visits (by boat) per low tide period, defined as the time from 2 hours before to 2 hours after low tide and allowing a modest travel time between each site by boat. The number of sites per sea loch chosen was 2 to 6 depending on the size of the loch, with the number of days per loch emerging as a result.

At each site a tape measure laid down the shore and shore elevation (height) recorded using a theodoloite. The vertical heights of the upper and lower limits of *Ascophyllum* were measured using the theodolite and measuring pole. Five locations were chosen within 10m of the transect line and the heights of the lowest and highest *Ascophyllum* plants were recorded. Three levels were identified within the vertical zone of *Ascophyllum*, corresponding to the mid-point of the zone and levels 0.5m above and below this mid-level. Four 0.5m by 0.5m quadrats (area $0.25m^2$), were placed randomly along a horizontal line perpendicular to the shore profile tape within 3m of the tape at each sample level, making a total of 12 quadrats per site. In each quadrat:

a. Four plants were selected at random and the length of the longest frond measured.
b. All plants with holdfasts within the quadrat were removed by cutting to within 3cm of the base (holdfasts were left to allow regeneration). Plants were sorted into species and put into numbered mesh bags for later weighing. Where necessary, bags of collected weed were immersed in seawater for some time to ensure a constant water content and so avoid bias due to differential drying in air through the period of emersion (Burrows and others, 2012).

Assessments of the harvestable resource of *Ascophyllum* in western Ireland used a hand-held portable Global Positioning System (GPS) and portable data-logger to record the following attributes: longitudinal and latitudinal co-ordinates,length (horizontal) of the bed being surveyed, depth (vertical) of the bed being surveyed, quality of the seabed, presence of other seaweeds (Hession and others, 1998).

Ascophyllum beds in Portugal were assessed using hand-held GPS to delimit bed perimeters and 50cm x 50cm quadrats used within beds to assess biomass (Borges and others 2020).

In Nova Scotia, the proportion of *Ascophyllum* biomass that can be harvested annually is established on a lease-by-lease basis by the provincial government and does not exceed 25%. Biomass estimates are audited by third parties and estimate the biomass of *Ascophyllum* so that sustainable harvesting quotas can be established for each lease area. Methodology to assess biomass has changed since its inception in the 1990s and is described by Lauzon-Guay and others (2021). Sampling was done during a 4-h window around low tide, using transect locations selected haphazardly within the main beds, attempting to obtain a representative sampling of *Ascophyllum* within each sector. Between 1 and 6 transects were deployed within each sector depending on the size of the sector. A transect line was deployed from the low water mark to the top of the *Ascophyllum* zone, perpendicular to the shore. Between five and fifteen 100 × 50 cm quadrats ($0.5 m^2$) were randomly positioned along the transect. In each quadrat, three clumps (a clump consists of all shoots originating from a common holdfast) were randomly selected and their height measured to the nearest 1 cm with a meter ruler. All of the *Ascophyllum* shoots were cut 15 cm away from the holdfast and weighed in a mesh dive bag using a digital hook. The mass of *Ascophyllum* above 15 cm from the holdfast per unit area is defined as the biomass. Over time, sampling methodology has been modified to obtain a more accurate estimate of the biomass within the central area of the beds (mid-intertidal) where most of the harvest takes place. All transects and all quadrats were positioned in the mid-intertidal zone in the 2010s. *Ascophyllum* is shorter and less abundant higher up on the shore: including quadrats from that location would have decreased the average height and biomass at each site. A 30-m transect line was deployed in the center of the A.*nodosum* zone, parallel to shore with ten 50 × 50 cm

($0.25m^2$) quadrats randomly positioned along the length of the transect. *Ascophyllum* height and biomass were still measured in a similar manner as in the 1990s, with 3 clumps measured for height per quadrat and all A. *nodosum* biomass 15 cm above the holdfast removed and weighed.

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Appendix 4 Dive survey

Description

Dive surveys are flexible and can provide habitat and species information using transects and timed searches, quadrat surveys and photo-quadrats. The information collected can include complete species lists (including information on where in the habitat they were observed, mean (± SD) and maximum abundance values for all species recorded in transects or quadrats (plus total abundance and richness), and habitat information obtained from video footage (e.g. density and coverage of species, composition and cover of kelp canopy).

Fixed sites can be re-located through GPS and on-surface location using conspicuous land features, lined up to create transits.

Dive surveys are frequently commissioned to ground truth the results of acoustic and other surveys or modelled predictions and estimates.

Equipment required

Trained dive personnel, diving and safety equipment, and suitable vessel coverage. Underwater stills camera or video. In the UK, a HSE diving contractor is needed for all commercial work. Typically, survey will use 4 HSE scientific divers and 1 supervisor.

Distribution mapping

Distribution of macroalgae can be mapped in the survey area, typically over a transect or belt line. Canopy forming species can be surveyed more readily than understorey algae or epiphytes.

Biomass estimation

For biomass estimations by dive survey, kelp plants are typically harvested from within a set area (i.e. 1 x 1 m quadrat) and then placed in bags or attached to lines and returned to the surface for identification and weighing. The number of plants harvested/quadrats clearer per dive is highly variable and depends on kelp species, depth, environmental conditions and diver experience, but about 10 large quadrats (i.e. 1 x 1 m) can be collected by 2 divers within a ~45 m dive. See Smale and others (2016) and Burrows and others (2018) for examples.

Costs

Costs are highly variable depending on vessel hire and diver experience and size of team. An estimate of £600/day for a basic dive team (i.e. supervisor, 2 divers) and £800 for a vessel would provide an indicative day rate of £1,400, but additional divers would likely be needed to complete survey work (at ~£200 ea per day).

Spatial coverage

Varies by size of dive team, approach, depth and local conditions, 10 replicate 1 x 1 m quadrats per dive 0.0001 km^2/hr (survey). Belt transects and surveys using photographs and video to record information will cover a wider spatial scale but are still relatively restricted compared to acoustic methods and AUVs.

Accuracy: Species identification

High accuracy but determined by skill and training of diver or quality of camera/video imagery and analysis.

Accuracy: differentiate kelps

High accuracy but determined by skill and training of diver or quality of camera/video imagery and analysis.

Accuracy: species density/condition

High accuracy but determined by skill and training of diver or quality of camera/video imagery and analysis.

Accuracy: species extent

Yes, but determined by skill and training of diver or quality of camera/video imagery and analysis.

Influence of environmental variables:

Weather conditions are key and periods of high winds and heavy rain will prevent surveys and reduce underwater visibility. In areas of high current speed or tides and wave action diving is limited to windows such as slack water.

Advantages:

- Allows collection of high-quality data
- Survey design and data collected is flexible,
- Can assess extent, distribution, abundance and biomass for selected species

Disadvantages:

- Generally spatially limited, divers cannot perform multiple dives ascending and descending throughout a day
- Carries risk to divers

Examples of studies and methodologies:

The structure of *L. hyperborea* populations was quantified along a depth gradient spanning 2–15 m (below Chart Datum) using traditional scuba diving techniques at eight sites in each of four regions (northern Scotland, west Scotland, southwest Wales and southwest England (Smith and others, 2022). Divers were deployed on a seaward-facing sloping reef habitat and descended to 15 m to commence survey work, after which divers ascended the slope and conducted surveys at 10, 5, and 2 m depth. At each depth increment, eight replicate 1 m^2 quadrats were haphazardly deployed on stable rocky substrata and the density of *L. hyperborea* was enumerated and recorded in situ. In each quadrat, the density and percent cover of both canopy-forming and subcanopy plants (defined as clearly identifiable digitated plants with stipe length > 5 cm) were recorded, as well as the density of sea urchins. Replicate quadrats were situated at least 3 m apart from one another, along the isobath of the targeted depth increment. In addition, divers noted the maximum depth of the kelp forest (defined as continuous stands of plants where gaps between plants were < 1 m) and of individual kelp plants (i.e., solitary plants situated > 1 m from the margin of the forest). Where maximum depths exceeded the 15 m isobath for quadrat surveys, divers continued to descend the slope to record maximum depth limits (to a maximum operating depth of 22 m).

The morphology and biomass of kelp plants were also examined by destructive sampling of individuals. At each depth increment, 10 canopy-forming plants were randomly collected. In the laboratory, a range of measurements were immediately taken (e.g., length and fresh weight biomass of the holdfast, stipe and blade, the age of individuals as estimated by cross-sectioning of the base of the stipe and counting growth rings).

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Appendix 5 AUVs/ROVs and remote camera surveys

Description

Remote camera surveys and drop-down video, towed video and combined video and stills drop-down or towed systems are widely used for underwater marine survey. The use of robots, either an autonomous underwater vehicle (AUV) or Remotely Operated Vehicle (ROV) is increasing. Drop cameras are generally cheaper, quicker, require less maintenance and are easier to deploy than AUVs and ROVs. They can be towed to follow a line to conduct transects but there is little control over position. Drop-down cameras can be fitted with laser scaling and other ancillary equipment such as CTD sensors.

An autonomous underwater vehicle (AUV) is an unmanned underwater robot, electrically powered by batteries, that operates independently of a surface vessel for a few hours to several days. AUVs are capable of collecting geophysical, biological and oceanographic data from both the seafloor and water column. The AUV will either follow a survey plan that is entirely pre-planned before the mission, or a combination of pre-planning and re-planning during mission, as smarter modes of control are developed. The data gathered is downloaded from the AUV when it has surfaced via a WiFi link and/or data cable.

Large AUVs used for ocean research are not feasible for inshore seaweed survey but small AUVs (typically < 3 m) are available that are relatively portable and can be manually deployed from shore or small vessels of opportunity reducing survey costs. The ability of cruising AUVs to fly at low altitudes (<5m) over the seabed, carrying high definition camera systems, coupled with developments in image processing, allows the generation of high volume imagery datasets that can be processed to provide continuous coverage georeferenced photographic datasets of the seabed (JNCC, 2018a).

Unlike an AUV, an ROV is connected to, and operated from, the water's surface via an umbilicus that transmits electrical power and command and control signals to the vehicle and sends a return video stream and telemetry (data signals) back to the surface operator(s). ROVs range in size from small, very portable observation class vehicles (<10kg) that are packaged in three suitcases and operated by a single pilot, to large ROV systems that would be unsuitable for inshore surveys.

All systems can carry a scale bar or laser pointers to provide a scale for camera images. AUVs and ROVs can (depending on payload) carry a range of sensors including navigation systems to provide positioning / geolocation data and environmental sensors.

Equipment required

Personnel. For drop down camera, small AUV/ROV 1-2 engineers/operators and vessel and crew.

Distribution mapping

Distribution and extent of macroalgae beds can be mapped within platform limitations around manoeuvrability.

Biomass estimation

Not directly. Analysis of video images can be used to estimate biomass.

Costs

Estimated cost per day, ROV £2,400-7,000; AUV £900-1,400 (based on 5-7 days) (JNCC, 2018a and b) based on planning, AUV or ROV and vessel hire, planning and day rate for on-board scientist/survey manager. Prices are likely to have increased.

Spatial coverage

Small Class I and II ROVs can conduct fine-to meso scale surveys (<25m^2 to <1km^2). AUVS can conduct surveys across broad areas (>25m^2 <1km^2) (JNCC, 2018). Drop down cameras have greater spatial coverage, 2km^2/day.

Drop down cameras or AUVs are a good option for initial exploration of broadscale areas to identify areas of interest with ROV or dive surveys commissioned to do higher resolution survey work thereafter.

Accuracy: Species identification

High accuracy from video and stills analysis in good conditions, overlap of canopy is likely to obscure understorey species, including small red seaweeds.

Accuracy: differentiate kelps

Yes, from video and stills analysis for all three methods.

Accuracy: species density/condition

High accuracy from video and stills analysis in good conditions, overlap of canopy is likely to obscure understorey species, including small red seaweeds.

Accuracy: species extent

High accuracy from video and stills analysis in good conditions, overlap of canopy is likely to obscure understorey species, including small red seaweeds.

Influence of environmental variables:

As with all optical surveys, turbidity will reduce visibility. Cruising AUVs are unsuitable for low altitude (<2m) surveys in complex high relief terrain without careful planning and high quality bathymetric data and are unsuitable for vertical and near-vertical surfaces (e.g. underwater cliffs) unless the vehicle is reconfigured.

All approaches will be limited by poor weather conditions and missions may be compromised in areas of strong tidal currents (at or above speeds of 1.5–2.0 m/s) and imagery capture will be affected by high turbidity.

Advantages:

- Remote camera surveys are much faster and generally less expensive than diver surveys.
- Can survey for longer, ascend and descend repeatedly (unlike divers), and visit multiple stations in a survey day.
- Can survey complex terrain, otherwise inaccessible by towed gear and grabs.
- Cruising AUVs can fly relatively close to the bottom (<5m altitude in areas of low relief),
- AUVs follow pre-set courses and can achieve more complex survey patterns and maintain precise altitude, speed and photo angle (pitch,
- AUV surveys can cover large areas and yield high volumes of quality imagery.
- Photographic survey coverage rate by AUVs is typically much greater than alternative methods (ROV or tow camera).

Disadvantages:

- A key disadvantage of towed camera systems is their lack of manoeuvrability, as there is limited control over position, altitude and speed of the camera. The tether to the vessel means that swell influences the camera position and this can lead to a large proportion of photographs being unsuitable for quantitative analysis (JNCC, 2018.

- In complex, high-relief terrain, cruising class AUVs are unsuitable to conduct low altitude surveys due to the risk of seabed collision
- ROVs and AUVs are more expensive to run than towed sampling platforms and are more prone to equipment failure/down time during surveys.
- Power is a limitation for the smaller Class I ROVs and their performance reduces with increased depth (due to tether drag), high current velocities and adverse weather conditions (JNCC, 2018b).
- ROVs are less rugged, and their area coverage per hour is much less than drop cameras and towed sleds (Eletheriou, 2013).
- Risk of entanglement and snagging in obstacles such as discarded fishing gear.
- Risks of damage / loss, especially in coastal/heavy human use environments; damage and entanglement from human (fishing gear, boat traffic, offshore structures) and natural (caves, ledges and macroalgae) sources.
- AUVs and ROVs need extensive technical support team to be able to fix them when it is damaged, physical failures delay/prevent missions e.g. incorrect component installations.

Examples of studies:

Smale and others (2012), used a modified SeaBED AUV to monitor hard coral and macroalgae habitats 15-40m deep at Rottnest Island and the Houtman Abrolhos Islands, Western Australia. Full coverage maps of nine areas 25 x 25m were produced from a dense grid overlapping 25m long transects. Using differential GPS, USBL, and image referencing technology, the AUV was able to relocate and survey the same area of seabed the following year.

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Appendix 6 Acoustic survey

Description

Sonar systems are either operated from boats where the sensor (transducer) is mounted on the hull, or towed behind in a ‘fish’. There are two basic types of sonar: single beam echo-sounders and swath sonars. Single beam echo-sounders emit a vertical cone of sound that ensonifies a discrete area of seabed (a circle in its simplest form) under the vessel. Swath sonars ensonify a strip of seabed perpendicular to the vessel, where the range either side of the vessel is dependent on the frequency of the sonar (Davies and others, 2001). The returning sonar signals are converted into digital information. In recent years, there has been significant progress in sonar and echo-sounder detection.

A Single Beam Echosounder (SBES) emits a pulse of sound of a fixed frequency and duration that is directed vertically towards the seafloor. The sound reflects from the seafloor back to the transducer, which then converts the sound energy back to an electrical signal and this signal is analysed as a time-trace of the energy. SBES’ are the simplest of the SONAR systems and analysis of the echo is much less complex than for swath systems such as sidescan and multibeam systems. Some systems integrate signal strength and time from particular sections of the echo to obtain information on the seabed. This is the basis of the commercial RoxAnn acoustic ground discrimination system (AGDS) (Davies and others, 2001). Although RoxAnn is designed to discriminate between habitat types, it has also been used for kelp habitat mapping (Hass and Bartsch, 2008).

Swath systems (sidescan and Multi Beam Echosounder MBES) have the benefit of much greater spatial coverage. However, the analysis of the signal from swath systems is not as straightforward as that from SBES. The UK Hydrography Office (UKHO) (now ADMIRALITY Maritime Products and Services), stores sonar multibeam data, surveyed for the entire coastline. When interrogated, this can be used to determine the location of kelp (McGonigle and others 2011).

Equipment required

Vessel and crew plus experienced operator.

Distribution mapping

An echosounder is practical to map density and height distributions of seagrass and seaweed beds. The side scan sonar is appropriate for mapping broad horizontal distributions.

Applications for surveys are:

- Broad-scale survey of large areas to map the approximate distribution and extent of habitats
- Identify areas of interest where there is a greater likelihood of finding a particular habitat
- Rapid repeat survey to assess changes over time.

Outputs can include depth, height of kelp canopy, signal strength under the canopy, percentage area (PAI) and percentage volume inhabited (PVI) (Burrows and others, 2018).

Biomass estimation

Extent and canopy height can be measured but biomass cannot be directly measured. However, Blight and others (2011) found a consistent relationship for all surveys between the stipe length of individual specimens of *L. hyperborea* and their total biomass (stipe and lamina mass), allowing a meaningful estimate of biomass to be derived from acoustic surveys.

Tanaka and Tanaka (1985) classified *Sargassum* beds along defined transects into different groups based on the canopy height on echograms, which were related to sampled biomass along one transect. They estimated the total biomass from the surface area of each group.

A similar approach trialled in Ireland found that the acoustically determined depth profile of the kelp beds showed a highly significant relationship with the data obtained from diver sampling and observations. A strong relationship was also recorded between diver derived kelp biomass and the acoustically measured coverage and height of the kelp above the substrate. The relationship between acoustic parameters and sampled biomass, obtained after smoothing, appears consistent and can be used to predict kelp biomass. The regression equation relating kelp biomass to the acoustic output obtained from data for the south-west surveys and applied to the acoustic data for the west coast survey, correctly predicted the higher biomass found on the west coast.

Costs

Ca. £3-5k per day to cover 2 km^2, based on 100m line spacing (Burrows and others, 2018).

Spatial coverage and resolution

Side scan sonar can cover 1-8km^2/hr while swath sonar cover 3-6km^2/hr (Davies and others, 2001).

Backscatter can distinguish small features such as tidally generated bedforms with wavelengths as low as 0.1m (Wynn and others 2014).

Accuracy Species identification

Can distinguish between canopy forming and filamentous seaweeds (Lubsch and others 2020), but distinguishing between species with similar properties is less feasible (Blight and others, 2011).

Accuracy: differentiate kelps

Acoustic surveys of Irish kelp beds found that it could not be used to distinguish between the two principal species of kelp, *L. hyperborea* and *L.digitata* (Blight and others, 2011).

Accuracy Species density/condition

Acoustic surveys in Ireland demonstrated a clear transition from dense kelp beds to sparse or barren areas at survey sites. Dense kelp would appear to be well defined spatially and the transition zone can be confidently mapped (Blight and others, 2011). Similarly,

Accuracy: species extent

McGonigle and others (2011) found that in the Gulf of Maine, the efficiency of prediction decreased with depth and that shallower Lamianria spp. Were more accurately mapped than a deeper water species (*Agarum cribrosum*).

Influence of environmental variables

Advantages

- Unlike optical imaging techniques is not limited by turbidity
- Provided accurate estimates of vertical length of kelp (*Saccharina latissimi*) grown on long-lines (Lubsch and others, 2020)

Disadvantages

- High acquisition cost of sonar equipment,
- Difficult treatment of the system on a small boat,

- Difficult processing of recorded imagery due to movement and position of boat, and seaweeds in currents and waves.
- Overlap of fronds reduces abundance estimates (Lubsch and others, 2020

Limitations:

- The detection, respectively quantification of seaweeds without air-filled vesicles still remains difficult and mostly resembles unchartered territory.

Examples of studies

A low-cost, commercially available Single Beam Echosounder (SBES) with modified signal-processing software was trialled to determine the spatial distribution of kelp in both wave-exposed and sheltered sites at two locations on the south and west coasts of Ireland and to relate derived acoustic parameters to verified estimates of kelp density and biomass provided from SCUBA diver ground truthing (Blight and others, 2011).

Jackson (2003) mapped seagrass beds around Jersey using a Biosonics echosounder and the correlation between results from the echosounder and from diver ground truth stations was found to be strong. Further, Collins (2009) briefly reported on a comparison between echosounder and video; with agreement between the systems increasing with increasing density of macrophytes - in this case, seagrass.

Assessing biomass of cultivated kelp, *Saccharina latissima*, on longlines, using sonar provided a good estimate of the maximum length of the cultivated plants (Lubsch and others 2020).

Single-beam sonar, has been used to detect kelp in Germany (Bartsch and others 2008), and to generate a variable of subtidal rock to use in SDM for kelp in France (Gorman and others 2012).

MBES has been used to estimate kelp biomass (Williamson and others 2012), and to monitor varying marine biotopes in Northern Ireland, including kelp beds (van Rein and others 2011), it was concluded that kelp monitoring can be successful with MBES acoustic techniques, ground truthed with video or dive surveys.

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Appendix 7 Unmanned Aerial Vehicles (UAV)

Description

The term Unmanned Aerial Vehicle (UAV) can be used to describe a diverse range of aircraft that are piloted from the ground. The aim of this document is to detail UAVs that are used routinely for marine benthic monitoring, less than 20kg in mass, and termed Small Unmanned Aircraft (SUA). In this context, they can be characterised as small, battery-powered aircraft, typically capable of flying for a short period of less than an hour under the control of a pilot within line of sight of the aircraft.

UAVs of <20kg are considered to be the most feasible (cost-wise) and practical class for marine ecological monitoring and represents the type of UAV that is most commonly used for conducting scientific surveys within marine and coastal environments (Anderson and Gaston, 2013)

UAV can be fitted with a wide range of sensors to capture data during survey flights. For example, fitting of imaging sensors (cameras) allows the system to acquire geo-referenced photographs and videos. These data can then be downloaded and processed by the end-user to create a range of outputs in order to meet survey objectives.

UAVs can capture imagery (red, green and blue (RGB), multispectral, hyperspectral, thermal, etc.) to produce still RGB images and video, still multispectral imagery, hyperspectral imagery, Light Detection and Ranging (LiDAR), and thermal imagery.

Survey flights can be planned to take advantage of low spring tides. Flight paths can be pre-programmed and repeated to generate multi-temporal datasets for change detection analysis, although radiometric correction must be applied to optical data to enable comparison between dates.

Fixed-wing UAVs

- Are typically utilised for speed and energy efficiency, covering comparatively longer distances and flight durations
- Typically stay airborne from 20 min to several hours

- Usually need a larger cleared area for take-off and retrieval. They normally require assistance with taking off (“throwing” by hand or catapult) and a capture system or smooth ground for retrieval (Colefax and others, 2018).

Multirotor UAVs

- Are a comparatively new technology and have only appeared in the marine literature in the last few years
- Utilised for vertical take-off and landing capabilities, requiring no additional landing equipment, making them also suitable for launching and retrieving from small vessels
- More dynamic and responsive in movement positioning
- Can sometimes provide better image stability and more accurate geo-referencing capability regarding a specific target
- Consequently, they are aerodynamically unstable and have shorter flight durations of typically 12–40 min.

For more information on the types of UAVs see (Anderson and Gaston, 2013).

Equipment required

At ground control: transportable hardware/software devices, digital data collection devices, phones or tablets with the relevant software downloaded (Baena and others, 2018).

Three-channel digital cameras that come standard with low-cost UAV platforms are less adept at classifying submerged kelp. Multispectral imagery i.e collected by a multispectral UAV payload has higher accuracy.

Distribution mapping

UAVs can collect still and video imagery or produce orthomosaic or reflectance maps to produce broadscale habitat or biotope maps through automated image analysis (object-based or pixel based) and support habitat condition monitoring.

Biomass estimation

Not directly. Multispectra UAV imagery combined with shore surveys (quadrat estimation of biomass) have been used to model predicted biomass (not UK).

Costs

Multi rotor cost per day approximately £500 to £1000 for fixed wing (based on JNCC, 2019 prices, these are likely to have increased).

Lower price ranges may not contain GPS/GNSS or have cameras of suitable quality and resolution.

Spatial coverage

Survey spatial coverage for fixed wing is typically greater (>0.25km^2 to <5km^2) than multi-rotor, (~0.25km^2 <2km^2) (JNCC, 2019).

Fixed-wing UAVs, civil aviation regulations in many countries restrict typical usage to “line of-sight,” effectively reducing potential range to a few kilometres. Whilst line-of-sight restrictions can currently be negated theoretically in certain locations and situations (on a case-by-case basis), in most operations it would likely be unfeasible. Specialized training would have to be obtained and proven safety countermeasures would have to be accepted by aviation authorities, such as collision avoidance with other aircraft, event of loss of signal or control, and systems failure. This may reduce potential benefits of fixed-wing UAVs, leaving multirotor as often the preferred option for UAV aerial surveys in scenarios where the survey area is relatively small, and where better manoeuvrability (including at launch and retrieval) and hovering capabilities are attractive (Colefax and others, 2018).

Accuracy: Species identification

In recent years, UAVs have been utilized to monitor intertidal macroalgal communities (Rossiter and others, 2020), monitor invasive aquatic vegetation (Bolch and others, 2021) and emergent kelp canopy (Saccomono and others, 2022).

Cameras that capture light from wavelengths outside of those visible to the human eye, such as near infrared, may be able to better detect submerged seaweed and differentiate between species. Image-derived spectra was the most accurate at classifying *A. nodosum* (94.7%, with SAM at 81.1%) and also other canopy-forming intertidal species, potentially making it more suitable than visible light images for a broader range of intertidal mapping objectives (Rossiter and others, 2020).

Diruit and others (2022), used a UAV to collect hyperspectral imagery (at 64m height). Seaweed habitats were successfully differentiated between fucoid species, substratum and seawater. However, technical limitations were apparent, because of their heterogeneous distribution on the rocky shore and mixed spectral signals due to similar spectra, or variations of spectra according to their health conditions (e.g., pigment degradation, grazing, occurrence of epi/endophytes) red and green seaweed species were difficult to differentiate (Diruit and others, 2022).

A study (Helgoland Germany) used a drone and specifically focused on the intertidal zone, analysed hyperspectral imagery from the rocky intertidal of Helgoland. Discrimination between red, green and brown seaweeds was possible but not to species level and separation of mixed vegetation types was limited (Hennig and others, 2007).

Accuracy: differentiate kelps

High resolution RGB imagery is an effective tool for feature identification (Rossiter and others, 2020). Can differentiate between near-shore kelp beds and land (a challenge associated with satellite) (Saccomanno and others, 2023). Kelps that form large floating canopies are relatively easy to distinguish using airborne imagery (Cavanaugh and others, 2021). Other common intertidal species can be spectrally distinguished (Rossiter and others, 2020).

Accuracy will partly depend on the classification system used and the quality of the ground truthing (training) data to support this.

Accuracy: species density/condition

Dense, homogenous beds can be readily distinguished on the shore but image processing and resolution will influence the degree to which less dense and heterogenous beds can be distinguished. Spectral signatures can vary between different condition states (Diruit and others 2022), and future developments may support condition assessments.

Accuracy: species extent

UAVs can capture small or sparse kelp beds and differentiate between near-shore kelp beds and land, addressing detection challenges associated with satellite imagery. Novel automated canopy detection algorithms have been shown to be highly accurate and the assessment of the influence of tides and currents has recently improved data collection and processing methods (Cavanaugh, and others, 2021).

Influence of environmental variables:

Weather conditions may restrict usage, particularly during periods of high winds and precipitation (most UAVs are not waterproof). UAVs can map and monitor benthic habitats in shallow coastal waters, but this requires clear, calm water with minimal sun glint (Kellaris and others, 2019). Penetration through water is dependent on prevailing conditions and limited by turbidity.

A study (Clew Bay Ireland) found that for every additional meter in tidal height the seaweed coverage that can be mapped is reduced by 18.7% and every additional 10m in drone height the coverage increases by 2.5%. Therefore, for most accurate results surveys should be performed at the lowest tide and from the highest elevation.

For surveys, the wind speed threshold for deployment is approximately 45 km/h for small quadcopters (Saccomanno and others, 2023).

Advantages:

- High spatial coverage and resolution (cm scale);
- Flying at lower altitudes (<100m) than traditional remote sensing methods, allows for data capture below cloud cover;
- Flexibility in timing of data collection, to allow for best conditions (weather, tides etc.) contrary to using satellite imagery (Saccomanno and others, 2023);
- Ability to survey areas that may be difficult to access (Rossiter and others, 2020); unsafe to survey using other methods or sensitive to disturbance (e.g. trampling under foot);
- Surveys often more cost effective than other methodologies;
- A high degree of repeatability, provided that radiometric correction is applied to
- Optical imagery to ensure consistency between surveys;
- Multiple data products can be produced from a single survey;
- Potentially reduced number of personnel required;
- Relatively low start-up costs and pilot training requirements (Saccomanno and others, 2023);
- Improvements in UAV sensor resolutions and alternative sensor types, such as multispectral and hyperspectral cameras, may increase area coverage, reduce perception error, and increase water penetration for sight ability (useful in turbid waters like that found in UK);
- Additionally, the further development of auto-detection software will rapidly improve image processing and further reduce human observer error inherent in manned aerial surveys; and
- Can often be used to access inaccessible areas although this feature is of less importance for harvesting studies which will focus on accessible shores.

Disadvantages:

- UAVs are more heavily regulated in the UK than other forms of marine monitoring platform (see JNCC, 2019);
- Civil aviation restrictions, and subsequent available civilian technologies, make it unlikely that UAVs will currently be more effective than manned aircraft for large area marine surveys (Colefax and others, 2018).
- Not yet cost or time effective for surveying large regions (state wide) (Saccomanno and others, 2023);
- The high power consumption and weight of hyperspectral sensors make the integration with UAVs difficult (Rossiter and others, 2020).
- Have to check licencing e.g if approx. 2kg the drone cannot fly over uninvolved people (Hayes and others, 2021).
- Visual line of sight requirements limit spatial coverage (Saccomanno and others, 2023).
- Telemetry link limitations (often 3–7 km) (Saccomanno and others, 2022).

- Maximum flight altitude restrictions (120 m without a waiver) (Saccomanno and others, 2023).
- Reliance on batteries with finite charge (Saccomanno and others, 2023).
- Difficulty in analyzing aquatic plants is that their spectra vary due to the dampening effect of water on the spectral signal (Oppelt and others, 2012).

Examples of studies:

Duffy and others (2018) used a small (i.e. <7kg) 3D Robotics Solo multi-rotor drone custom-mounted with a consumer grade camera (Ricoh GR II) to capture detailed imagery data of intertidal seagrass (*Zostera noltii*) meadows at two sites in Pembrokeshire, Wales. At each site an area of ~2500m^2 was surveyed using the 'lawnmower' method (running parallel lines along the length of the survey area in alternating directions). The use of an autopilot system, open-source firmware and flight planning software allowed for complete control of the flight to ensure optimal data outputs. The survey successfully captured total of ~200 usable images at each site, during flights of <11 minutes.

Murfitt and others (2017) compared UAV remote sensing of intertidal reefs (Australia) to traditional on-ground monitoring surveys and investigated the role of UAV derived geomorphological variables in explaining observed intertidal algal and invertebrate assemblages. A multirotor UAV was used to capture <1 cm resolution data from intertidal reefs, with on-ground quadrat surveys of intertidal biotic data for comparison. UAV surveys provided reliable estimates of dominant canopy-forming algae.

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Appendix 8 Aircraft (manned aerial vehicles)

Description

One of the most commonly used methods for monitoring intertidal seaweeds and nearshore surface-canopy kelp is aerial photography, a technique that dates back to the 1920s (Guillaumont and others 1997). Several different photographic techniques are used, including infrared and visible light (RGB) photography.

Topo-bathymetric lidar measures the three-dimensional aspects of the seafloor and what is in the water column, offering the potential to derive height metrics for seaweed as well as the surface area. Topo-bathymetric lidar is an active sensor that relies on two lasers; a green laser beam emitted from the aerial sampling platform to penetrate the water column and reflect off the seabed or submerged objects such as vegetation and reflect back to the sensor, and a near infra-red laser for the topography and to determine the water surface (Webster and others 2016). This information is translated into a three-dimensional point cloud of the seabed.

Equipment required

Aircraft, personnel, minimum a pilot.

Distribution mapping

High resolution aerial photography has the capability to determine the spatial extent of subtidal kelp beds but is depth limited. Good quality colour aerial photographs taken at low water of spring tides at a scale of 1:10,000 provide the best information for shore mapping. Photographs taken at a larger scale may not show enough detail to be useful (Davies and others, 2001).

Webster and others (2019) evaluated top-bathymetric LiDAR (light detection and ranging) as a tool for estimating the surface area, height and biomass of *Ascophyllum*, and compared the surface area derived from LiDAR and WorldView-2 satellite imagery. This study demonstrated an innovative and cost-effective approach that used a single, high tide bathymetric LiDAR survey to map the height and biomass of dense macroalgae

Biomass estimation

Indirectly from imagery or LiDAR.

Costs

Estimated time for processing aerial photos was six days maximum to evaluate each 5km x 5km square, allowing for 1 day of ground truthing (Davies and others, 2001).

Spatial coverage

Broadscale.

Accuracy: Species identification

No, accurate species identification is limited by low resolution of aerial imagery. Species level identifications will not be possible, but broad scale habitats (dominated by one or more species) can be distinguished (Yesson and others, 2015)

Accuracy: differentiate kelps

Accurate differentiation limited by image resolution.

Accuracy: species density/condition

Useful for mapping broad-scale, homogeneous *Ascophyllum* and shallow, canopy forming kelp. Aerial photographs do not allow the number of individuals to be quantified, they do yield metrics of extent (typically m^2 or ha of kelp) that should be proportional to population size (Britton-Simmons and others, 2008).

Accuracy: species extent

Aerial images can be extremely useful for determining distributions of large habitats at local scales.

Influence of environmental variables.

Aerial photography is reliant on good weather conditions and is also depth limited. The timing of photographs with respect to tides is also important. Tidal currents that subduct the canopy due to drag will also influence accuracy. Plants that are submerged deeply by currents are not visible in aerial photographs (Britton-Simmons and others, 2008).

The colour of the substratum will affect discrimination of beds for visible light imagery.

Advantages:

- Manned aircraft are cost effective for sampling large areas;
- Aircraft may afford higher spatial resolutions than satellites (but note satellite resolution is improving)

Disadvantages:

- Restricted operational flexibility to map small areas;
- Resolution is generally insufficient to map mixed macroalgae beds (Kellaris and others, 2019);
- Higher costs e.g. need to hire aircraft and a pilot; and
- Limited to the vicinity of airfields, are costly, and are subject to sight ability errors.

Examples of studies:

In a study testing the capacity of aerial versus satellite images to detect seaweed habitat, data from CCO, Bing Maps aerial images, RapidEye satellite images, and Landsat (8) satellite images were compared, with the CCO providing the highest resolution (0.1m), tide-specific, best estimates of habitat extent (Yesson and others 2015).

In Alaska, Stekoll and others (2006) used multi-spectral imaging captured using a plane flew at 731m which produced a resolution of approximately 0.3m. The approach could not distinguish between *Nereocystis* and *Alaria fistulosa* and there was significant variability in the canopy colour of the two species in different areas of the study site.

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Appendix 9 Satellite sensors

Description

Earth orbiting satellites can be used for operational tasks such as continual monitoring, forecasting and management of the marine environment. Satellites can provide high-resolution data, with imagery from multi-spectral sensors and infrared band, useful for vegetation surveys. Hyperspectral data obtained from satellites have been used to detect submerged kelp (Bell and others, 2015) and intertidal seaweeds. Using satellite and aerial imagery is a relatively new technique and the accuracy depends on type of satellite, sensor capability and resolution and used.

- Satellites can carry a variety of sensors: infrared, microwave, visible-light, magnetic field and radar altimeter systems being the most common;
- Sensors are generally restricted to the top few meters (or tens of meters;
- Image resolutions vary from 1 to 120 meters, according to the altitude of the system the operational bandwidth of the sensor, its velocity and its data capture rate.

A drawback to satellite data is the extensive processing required to extract information from the acquired images and the technique does not replace the need for direct surveys to validate (ground truth) the results.

Distribution mapping

Satellites are suitable for mapping intertidal algae in particular (Brodie and others, 2018; Setyawidati and others, 2018). For intertidal macroalgae and kelps that form surface canopies, the Landsat series of satellites provides a record back to 1983 at 30-m resolution (Cavanaugh and others, 2011; Nijland and others, 2019) and more recent satellites provide even higher resolution (Cavanaugh and others, 2010).

However, canopy-forming kelps on low-contrast bottoms or in deeper or turbid water can be difficult to see from the air, and some canopies vary in visibility with tides. Kelps can now be detected to a depth of 6 m (Uhl and others, 2016), but this only covers a portion of their depth range and turbidity will influence the actual depth cut-off.

Biomass estimation

Indirect estimation of biomass from imagery has been attempted. Cavanaugh and others (2021) estimated the canopy biomass of giant kelp from Landsat 5 Thematic Mapper satellite imagery, at 30 m resolution across the Santa Barbara Channel (California) every 1 to 2 months for 25 years (1984 to 2009). Spatial coverage of kelps was used to scale-up biomass estimates using field data collected by divers. Changes in regional kelp biomass were rapid, and order of magnitude increases and decreases in regional mean biomass routinely occurred over a span of <4 mo. The study found that winter loss of kelp biomass was correlated with extreme wave heights.

Equipment required

The number of satellites in orbit is increasing and the resolution of sensors is improving. There are a number of routes for obtaining satellite imagery, some require direct payments, others provide subscriber services and other sources may be free. An image from the Channel Coastal Observatory is shown below (Figure 2).

None for deployment, this technique refers to image acquisition for processing. Images can be acquired from a wide range of sources and some are freely available, the list below provides examples but is not comprehensive:

- Earth Explorer interface: NASA's EOSDIS data (Earth Observing System Data and Information System) (freely available);
- Channel Coastal Observatory (CCO): visible light and infrared (freely available);
- NOAA CLASS (Comprehensive Large Array data Stewardship System), users can select resolutions e.g. 1 m^2 or 4 m^2 (freely available);
- Landsat (resolution at 30m not sufficient for identification) (freely available);
- Google Earth, free satellite images come from Landsat-8 as well as aircrafts, drones, kites, and balloons;
- RapidEye satellite data provide five spectral bands (blue, green, red, red edge, and near infrared) at 5 m^2 resolution (freely available)
- Bing maps (http://www.bing.com/maps/) provide free access to aerial image data (with a resolution of 0.6 × 0.6 m) collected by Digital Globe via their representational state transfer (REST) interface;
- PlanetScope Satellite Constellation, 200 satellites weighing only 5.8 kg each, provide 3 m multispectral image resolution (paid service);
- SkySat constellation, c.20 satellites providing resolution of 50 cm^2 (visible and near infrared) (paid service).

Costs

Image purchasing costs are dependent on the source and type of imagery and the degree of processing required. Many sources

Spatial coverage

Satellite image resolution varies (Webster and others, 2020), examples of resolution are provided in the list above.

Accuracy Species identification

The spatial, spectral and temporal resolutions of satellite imagery can present several limitations. Emergent kelp canopies that are adjacent to the coast or offshore rocks are missed due to the reflectance properties of these terrestrial features within overlapping pixels (Hamilton and others, 2020; Nijland and others, 2019).

Accuracy: differentiate kelps

Dependant on resolution and satellite imagery equipment. Due to its relatively poor spatial and spectral resolution, multispectral satellite remote sensing is incapable of discriminating to species level but can map extent in shallow areas.

Accuracy Species density/condition

Density accuracy is quite high when using the coefficient of reflection which measures the reflection of light back from source.

Accuracy: species extent

Landsat data are helpful for understanding long-term, regional-scale kelp canopy dynamics, but the 30 m sensor resolution is often too coarse to accurately assess local-scale, spatial patterns (Saccomanno and others, 2023). Other satellites provide better resolution and World View 2 satellite data was sufficient to map the extent of *Ascophyllum* with overall accuracy greater than 80% (Webster and others, 2020)

The often moderate pixel resolution necessitates the use of a classifier to assign the class of each coastal pixel. The conservative nature of many classifiers may lead to the misclassification of sparse kelp canopies as seawater, thus missing small refugia that may be important to restoration efforts during periods of low canopy cover.

Influence of environmental variables

Most satellite imagery is not collected on demand, acquisition may occur during suboptimal periods, such as cloudy days or during high tidal height and/or current speed conditions, which can submerge emergent kelp canopy below the sea surface (Britton-Simmons and others, 2008; Cavanaugh, and others, 2021).

Advantages

- Target species can be monitored regularly.

- Most efficient methodology combines AUV's, in-situ sampling and dry weight giving a more accurate biomass
- Red, Green and brown seaweed beds in shallow water can be identified and mapped.

Disadvantages

- Satellite imagery can be affected by meteorological conditions, such as cloud and aerosol interference, surface glare, and poor synchrony with tides;
- Costly for higher resolution images particularly for identification purposes;
- Any image-based habitat classification will be based on the canopy only;
- Sensor penetration through the water column can be a problem. Not all species can be identified;
- Species of the same genus difficult to separate; and
- Good for a wide range of an identified species but accuracy difficult to guarantee.

Examples of studies

Casal and others (2011), successfully used multispectral satellite images to detect intertidal and subtidal kelp biomass from the Galician coast (NW Spain). Kelp biomass was verified with physical dives; the coarse resolution meant that Laminariales could not be distinguished from other seaweeds. Habitats were correctly assigned in almost 90% of cases, incorrectly classified areas were usually assigned to the submerged sand or emerged rock classes.

Cavanaugh and others (2010), commented that in general, species-specific differences exist in canopy structure of kelp, alongside variations in responses to tides and currents, and therefore any satellite mapping methodology should be developed specifically for the target species

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