Remote sensing of kelp (Laminariales, Ochrophyta): monitoring tools and implications for wild harvesting

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Abstract

Kelps (Laminariales, Ochrophyta) are ecologically and commercially important habitat-forming brown macroalgae, found in coastal ecosystems worldwide. Their presence in the sublittoral fringe makes monitoring kelp forests problematic and consequently they remain relatively understudied. Remote sensing offers new avenues to monitor difficult-to-access biomes, particularly kelp habitats, but previous monitoring efforts have only been tested on an ad hoc basis and a standardised protocol for monitoring kelp requires development. In view of on-going and emerging threats to kelp, there is a need for monitoring to establish detailed baseline information. Wild harvesting of kelp is increasing, illustrated by growing numbers of seaweed and seaweed-containing products. Simultaneously, climate change is causing sea-surface temperatures to rise and influencing kelp distribution and abundance globally. This study reviews the potential for remote sensing in macroalgal studies, with an emphasis on kelp and provides a conceptual framework to support the development of standardised monitoring protocols. Satellite-born sensors and aerial photography have been effective, but these distant sensors cannot operate effectively in turbid temperate waters, and many image surveys do not account for changing tides. Advances are being made in acoustic monitoring, particularly multibeam sonar. With some development, there is great potential for a standardised monitoring protocol for kelp, aiding management and conservation efforts.

Key words: Kelp, Laminariales, macroalgae, monitoring, remote sensing, seaweed harvesting

Highlights

- Remote sensing technologies available for monitoring kelp resources are reviewed.
- Environmental, ecological and anthropogenic pressures impacting kelp habitats are outlined.
• A conceptual framework to aid the development of standardized monitoring efforts is provided.

1. Introduction

Kelps are large brown macroalgae (seaweeds) characterised by a long stipe and broad fronds (Bartsch et al., 2008), they provide the largest (non-colonial) biogenic structures found in benthic marine systems (Dayton, 1985) and are features of coastal ecosystems worldwide (Tegner and Dayton, 2000; Steneck et al., 2002; Teagle et al., 2017). Socio-economically, kelps support valuable commercial fisheries (Blamey and Bolton, 2017) and are harvested around the world (Chung et al., 2017) for a variety of uses (e.g. food, alginates, medicines and fertiliser) (Buschmann et al., 2017; Mac Monagail et al., 2017). Further information detailing the ecological and socio-economic importance of kelp and kelp-based habitats is presented in Table 1.

Currently, kelps are under a range of threats, primarily from climate change (Smale et al., 2013; Brodie et al., 2014), but also new and increasing pressures i.e. from wild harvesting (Mac Monagail et al., 2017). Little knowledge of kelp distribution and abundance exists in a time when changing distributions have been noted (Yesson et al., 2015b), and wild harvesting is intensifying (Netalgae, 2017). This is largely attributed to the logistical difficulty of accessing and therefore monitoring kelps, due to their position in the shallow, rocky sublittoral fringe (Yesson et al., 2015b). A summary of several pressures impacting kelp habitats is given in Table 2. In this review the authors examine: i) the application of ground surveys and species distribution models (SDMs) to monitor kelp habitats, ii) remote sensing strategies available to monitor kelp distribution and abundance, and iii) provide a conceptual
framework to aid future kelp monitoring based on current remote sensing technologies,
increasing harvesting of wild kelp resources and a selection of other pressures impacting kelp
habitats.

1.1 Baseline information
Compared to the rocky shore intertidal, kelp forests in the rocky sublittoral fringe and
shallow subtidal have received little attention (Smale et al., 2013), to which a contributing
factor is likely accessibility. In recognition of this inequality, kelp forests have been receiving
greater attention in recent years (Yesson et al., 2015c; Young et al., 2015; Krumhansl et al.,
2016; Vergés et al., 2016; Smale and Moore, 2017; Teagle et al., 2017).

Baseline information of standing stocks is vital to the successful creation and implementation
of any ‘standard’ or ‘best practice’ guide for wild harvesting (Yesson et al., 2015b), but kelp
resources remain without baseline data at a time when threats to their global distribution are
increasing (Smale et al., 2013; Krumhansl et al., 2016) (Table 2). The need for baseline
information of kelp forests has been gaining recognition (Yesson et al., 2015c; Yesson et al.,
2015b; Krumhansl et al., 2016). Attempts have been made in southern Australia (Connell et
al., 2008) and the British Isles (Yesson et al., 2015b) to obtain such information based on
historical records. Historical records tend to have a significant degree of uncertainty
(Newbold et al., 2010) and coarse resolution estimates of abundance (based on inaccurate
occurrence data) cannot provide spatially detailed information for management and
conservation purposes. Moreover, the estimation of seaweed standing stocks via traditional
methods is difficult (see above), and often inaccurate with large margins of error (reportedly
up to ±40 % in some cases) (Mac Monagail et al., 2017). A rapid assessment technique is
therefore necessary, to overcome monitoring difficulties related to kelp forest ecosystems,
and provide detailed baseline information of standing stocks, which estimates based on historical records and traditional surveys have thus far, failed to provide.

### 1.2 Ground Surveys

Direct physical sampling is the foundation of current knowledge of kelp distributions. There will always be a need (and desire) to conduct site visits and collect specimens and (or) field data, for example, many remote sensing applications require direct sampling (i.e. ground-truthing). However, many complications are associated with direct surveys of kelp. Rocky substrata, challenging weather and dangerous currents are just some of the testing conditions which often characterise kelp habitats. Given that kelp habitats are relatively inaccessible, ground surveys are both logistically difficult and labour intensive. For this reason there is also a limit to the spatial extent that can be monitored effectively by traditional surveys (Zhi et al., 2014; Strong and Elliott, 2017) and it is likely that large areas of kelp in the subtidal routinely go undetected (Mac Monagail et al., 2017).

### 1.3 Species Distribution Models

Where observations are limited, species distribution models (SDMs) offer a method to extrapolate spatially restricted observations to apply throughout entire landscapes (Young et al., 2015, and references therein). SDMs can be especially useful in the marine environment where extensive sampling is considerably more challenging. Observations of occurrence can be associated with environmental variables to generate predicted suitable habitat and distribution estimates for kelp (Pauly and De Clerck, 2010; Yesson et al., 2015b). Depth, irradiance, water clarity and sea surface temperature can be effective predictors of kelp distributions (Birkett et al., 1998; Pauly and De Clerck, 2010). Given the lack of directly observed data available for kelp, SDMs offer a useful indirect method for estimating
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 et al., 2010; Gorman et al., 2013). Moreover, SDMs based on limited records that vary in reliability can lead to less reliable predictions (Proosdij et al., 2016). Another important consideration, highlighted by Cord et al. (2013), is the need to bridge disciplinary perspectives between modelling species distributions and remote sensing information. The authors make note of the increasing frequency of these disciplines merging, but point out that the need for caution when integrating remote sensing information and SDMs (Cord et al., 2013). In contrast, the use of good quality data in the form of environmental variables (relevant to the life history of target species) and extensive training data can offer more reliable predictions. For example, (Young et al., 2015) found improvement in prediction success when multibeam sonar and LiDAR were used together to predict kelp distribution and abundance.

1.4 Remote sensing

Recently, there has been a move towards monitoring difficult-to-access biomes, including kelp ecosystems, using remote sensing (Brown et al., 2005; Anderson et al., 2008; McGonigle et al., 2011; Mielck et al., 2014; Young et al., 2015). Coastal ecosystems have been monitored using multispectral imagery (e.g. Chen et al., 2011; Bell et al., 2015; Pan et al., 2016), aerial imagery (Anderson et al., 2007; Bendell and Wan, 2011; Bell, 2015; Uhl et al., 2016), light detection and ranging (LiDAR) (Tulldahl and Wikstrom, 2012; Wannasiri et al., 2013; Zavalas et al., 2014) and sound navigation and ranging (SONAR) (Komatsu et al., 2003; McGonigle et al., 2011; Mielck et al., 2014; Young et al., 2015). Remote sensing technologies are rapidly evolving and these advances are routinely being applied to marine
habitat monitoring, particularly UAVs (unmanned aerial vehicles) (Ventura et al., 2016; Casella et al., 2017; Murfitt et al., 2017; Ventura et al., 2017).

Furthermore, the availability of open-access (free) data from governmental and non-governmental agencies significantly reduces costs associated with data collection. Compared to traditional field surveys, remote sensing allows for the monitoring of a much greater geographic coverage. Methods can be standardised, and therefore, replicated, offering a more robust assessment which is significantly more reliable than comparatively patchy ground surveys.

2. Remote sensing technologies

Remote sensing is the “observation of a target by a device, separated from it by some distance” (Barrett and Curtis, 1976). This covers a wide variety of platforms and sensors. Information can be obtained from satellites via multi-spectral sensors, aircraft via aerial imagery/LiDAR, ships via sonar and underwater imagery via autonomous underwater vehicles (AUVs) or drop/towed cameras (Table 3). Remote sensing can permit assessments of areas that are difficult to access in person, such as the rocky sub-tidal zones where kelp often occurs (Silva et al., 2008). In the past, the study of ecology was largely qualitative but due to a concerted effort, there has been a shift in approach towards quantitative modes of study (Elith and Leathwick, 2009), giving rise to more robust assessments of ecosystem condition. Traditionally seabed information was limited to point observations (Zhi et al., 2014; Strong and Elliott, 2017) where data were gathered using labour intensive techniques such as grab sampling. The development of remote sensing technologies has allowed for extensive areas of seabed and coastal habitats to be mapped and assessed with dramatically
reduced labour. Additionally, these indirect methods are advantageous due to their expansive spatial coverage, cost-effectiveness, speed and quantitative nature (Casal et al., 2011; Yesson et al., 2015a). Disadvantages exist too: remote sensing surveys can be adversely affected by weather, and data collection can be complicated by atmospheric conditions (i.e. cloud cover). Sensors can also encounter difficulty penetrating deep, turbid waters (Ehrhold et al., 2006), and processing large quantities of remotely sensed data can be a time consuming process (Yesson et al., 2015a).

2.1 Satellite-borne sensors

Satellites can provide continuous global coverage from a number of multispectral sensors including infrared bands, which are useful for vegetation surveys (Pauly and De Clerck, 2010). Hyperspectral data obtained from satellites have been used to detect submerged kelp and assess biomass and physiological condition (Bell et al., 2015). Spectral signals have been shown to differ dependent on stress, suggesting that satellite imagery could potentially be a useful tool for detecting kelp disease or desiccation (Fyfe, 2003; Silva et al., 2008). In ideal conditions, where studies are in clear tropical water, surprising detail can be discerned, for example, seagrass can be detected with a spectroradiometer, displaying differences between clean and fouled leaves (Fyfe, 2003).

Cavanaugh et al. (2010) noted that in general, species-specific differences exist in canopy structure of kelp, alongside variations in responses to tides and currents, so that satellite mapping methodology could be developed specifically for the target species. Brodie et al. (2018) add that depths at which kelp is found can cause problems with detection, exacerbated by tides. Overall, satellite images are useful, but are often not targeted at coastal regions, and may not account for tides during data acquisition (Holmes, 2015; Yesson et al., 2015a). The
practicality of satellite-sensor data are regionally dependent, being considerably more
effective in tropical areas with reduced turbidity, compared to temperate regions i.e. the
northeast Atlantic. Multispectral satellite imagery has been used successfully to map kelp
distribution in turbid waters (Casal et al., 2011), verified with dive sampling. Nevertheless,
differentiation of Laminariales from other macroalgae remains problematic.

2.2 Aerial imagery

Light aircraft and unmanned aerial vehicles (UAVs) can capture aerial images at finer
resolution than satellite images (due to their relative proximity). This can be advantageous for
quantitative analyses (Yesson et al., 2015a). The rate of use of aerial imagery to map, assess
and monitor coastal habitats has been increasing as technology has evolved (Bendell and
Wan, 2011; Klemas, 2015; Ventura et al., 2016; Ventura et al., 2017).

Aerial images are, in general, of finer resolution (typically pixels represent sub-metre scales)
than satellite imagery (typical pixels are multi-metre), which can have important implications
for coastal analyses (Brodie et al., 2018). In Alaska, Stekoll et al. (2006) used multispectral
aerial imaging to estimate kelp biomass suitable for harvest, and encountered issues
pertaining to tides. Aerial surveys can also be hampered by inclement weather, which limits
visibility and can prevent flying. Additionally, turbid waters can hinder detection capacity,
particularly at the deeper end of the kelp depth range (Bartsch et al., 2008). Recent
developments in UAV (drone) technology, i.e. improvement of image resolution, reduction in
size, cost and ease of use, has encouraged the application of drones to coastal habitat
monitoring and assessment. UAVs have also been adapted to carry multiple sensors including
hyperspectral imagers, LiDAR and thermal imagers (Klemas, 2015). Consequently, the
current momentum of technological development in the form of UAVs is an exciting prospect
for the future of remote sensing in coastal ecosystems, from surveying marine megafauna (Hodgson et al., 2013) to constructing 3-dimensional maps of submerged coastal habitats (Ventura et al., 2016).

2.3 Underwater imagery

Underwater optical imagery involves the collection of image data using cameras. These can be deployed manually from dive surveys and manned underwater vehicles (MUVs), they can also be deployed remotely, either tethered to a vessel (i.e. a towed camera), or from unmanned surface vehicles or autonomous underwater vehicles (AUVs). Underwater imagery has previously been applied successfully to monitor benthic environments for ecosystem-based fisheries management (Smale et al., 2013) and to detect kelp (Bewley et al., 2012). Principally, AUVs have advantages over other imaging methods as they are less constrained by sea state and are capable of gathering high-resolution images of the benthos for use in habitat monitoring in previously inaccessible areas (Singh et al., 2004). The direct visualisation of benthic habitats is also advantageous as it allows the classification of biogenic habitats, associated biota and interactions therein.

Despite these advantages and the evolution of image collection technologies, the conversion of imagery into quantitative information remains difficult and labour-intensive (Bicknell et al., 2016). The physical position of underwater imagery techniques (in the marine environment) offers an opportunity to gather a combination of environmental data when used in conjunction with multiple sensors (Bicknell et al., 2016) (e.g. temperature, conductivity and salinity probes). Similar to ground surveys, underwater imagery does not offer rapid assessment of benthic habitats on a large geographic scale. Underwater imagery in this sense is not a true remote sensing technique, given the need for the sensor to be in direct proximity
of the target habitat. Therefore, as a method for kelp monitoring it shares many of the characteristics, and in turn, shortcomings associated with traditional ground surveys.

2.4 LiDAR (Light Detection and Ranging)

LiDAR derives structural information using a high-frequency light pulse and interpreting differences between return times of each beam (Holman and Haller, 2013). Resultant 3-dimensional datasets have been used to effectively detect aquatic vegetation (Rosso et al., 2006; Silva et al., 2008). Although an extremely valuable tool for ecologists, there remain pitfalls to its application as a stand-alone remote sensing technique for monitoring kelp abundance and distribution. LiDAR has proved to be a successful tool in terrestrial systems (Lefsky et al., 2002), but is limited in the marine environment by the capacity of light to travel through the water column, a problem that is exacerbated in turbid waters (Young et al., 2015). A combination of technologies is therefore required to ‘fill the gap’ which LiDAR cannot. As with many other remote sensing techniques, it is recommended that LiDAR data are properly calibrated and validated with ground-truthing (Silva et al., 2008).

With the development of bathymetric LiDAR, a number of studies have combined benthic terrain analysis techniques with LiDAR-derived information to detect submerged aquatic flora. Recently, the potential effectiveness of LiDAR-derived information for use in ecological assessments has been demonstrated in a variety of aquatic ecosystems, from mangroves (Wannasiri et al., 2013) to coral reefs (Brock et al., 2004) and macroalgal habitats (Zavalas et al., 2014).

2.5 Sonar (Sound Navigation and Ranging)
Surface-deployed acoustic sensors can be used to determine water depth and create a detailed picture of seabed morphology, including the detection of habitat forming organisms (Anderson et al., 2002; McGonigle et al., 2011; Young et al., 2015). Sound is more efficient at travelling through water than light, and can penetrate hundreds and even thousands of metres of water, even in more turbid, temperate regions. Practically, sound-based sensors are different from aerial and satellite systems, because they need to be based in (or on) the water. Although limited by depth, some high-resolution surface-based acoustic sensor devices can provide <5 cm resolution at even the deepest recorded kelp-depths (Pailhas et al., 2010).

Sonar acoustic monitoring offers an alternative to previously mentioned remote sensing techniques, processing backscatter information from an echo sounder can give a visual output from which it is possible to determine the composition of the seabed and visualise 3-dimensional habitats, such as cold-water corals (De Clippele et al., 2017) and submerged vegetation (Silva et al., 2008; Brown et al., 2011; McGonigle et al., 2011). Acoustic backscatter is the amount of energy received by a sonar device reflected from the seafloor. It can be used to determine seafloor substrata characteristics i.e. hard substrata will reflect more energy, whereas soft substrata will absorb more energy. Moreover, topography will also affect backscatter intensity as rough, uneven substrata will ‘scatter’ sound energy and flat, even surfaces will reflect more energy back to the device. In the past, backscatter information had been perceived as a bi-product of bathymetric data. In recent years however, the potential use of acoustic backscatter to classify substrata and habitat type has been recognised (reviewed in Brown et al., 2011).

Both single-beam and multi-beam sonar can be used to detect marine vegetation, with the former emitting one beam and a receiving transducer processing the time it takes for the signal to return, discriminating between different parts of the returning echo, and visualising
the results on a sonogram. Single-beam echo sounders and acoustic ground discrimination
systems (AGDS), such as the RoxAnn brand processor, have been used to map the marine
benthos in Scotland (Downie et al., 1999), to detect kelp in Germany (Bartsch et al., 2008)
and the Republic of Ireland (Blight et al., 2011), and to generate a variable of subtidal rock to
use in SDM for kelp in France (Gorman et al., 2013). All data still require ground-truthing
validation, through videography or grab-sampling (Humorstad et al., 2004; Brown et al.,
2011; Pergent et al., 2017). Multibeam sonar, which is more expansive and has greater data
volume than its single beam equivalent, can produce comprehensive seabed maps. Preferred
by fisherman for their increased ability to detect shoals of fish, multibeam echo sounders
(MBES) have evolved dramatically in the last 30 years, as have methods for analysing
acoustic backscatter (Brown and Blondel, 2009; Jones et al., 2010; McGonigle et al., 2011;
De Clippele et al., 2017).

Sonar has been used to estimate kelp biomass (McGonigle et al., 2011; Young et al., 2015),
to map seagrass distribution (Komatsu et al., 2003; De Falco et al., 2010; Pauly and De
Clerck, 2010) and to monitor benthic habitats (Ehrhold et al., 2006), but the success of the
seabed classification is dependent on the type of acoustic system used and the target biotope
(van Rein et al., 2011). Ground-truthing is integral to automated habitat recognition (Downie
et al., 1999; Ehrhold et al., 2006; Casal et al., 2011; Gorman et al., 2013; Yesson et al.,
2015a). Previous efforts have demonstrated that monitoring kelp distribution can be
successful using acoustic techniques, validated by ground-truth information, but despite past
achievements a fundamental issue remains: a standardised, transferrable method for
monitoring kelp resources still requires development.
3. Discussion

Direct surveys of habitats are the gold standard, but the practicalities of accessing coastal habitats mean that large scale monitoring through direct surveys will remain challenging. Efforts to increase the breadth of surveys, such as citizen science initiatives are unlikely to fill the data deficit in remote locations. SDMs based on historical occurrence data attempt to compensate for a lack of records, predicting distributions and suitable habitat to direct future explorations. While these can give broad ranging estimates of distribution, they are not a substitute for monitoring and are not appropriate tools for monitoring change. Remote sensing offers great potential for monitoring large areas. Whilst multispectral, aerial and underwater imagery have shown promise small-scale in many studies, new avenues are being explored in acoustic monitoring, particularly multibeam sonar, and are proving effective. Although, to-date, these have only been tested on an ad hoc basis, and a standardised rapid assessment protocol for monitoring kelp requires development. The findings of this study are summarised in Fig. 1 and Table 3, where information regarding the selection of appropriate remote sensing tools is summarised.

3.1 Citizen science

Citizen science can be an extremely valuable tool for researchers, particularly those investigating intertidal rocky shores, which tend to be logistically difficult and time consuming to monitor (Cox et al., 2012). “A citizen scientist is a volunteer who collects and/or processes data as part of a scientific enquiry” (Silvertown, 2009). Additionally, a 'symbiotic' relationship can arise between scientists and members of the public where, if adequate explanation and training is provided, citizen science can be beneficial to both parties as an interactive outreach tool (Newman et al., 2012). An example of a successful citizen science tool can be found in Galaxy Zoo.
(https://www.zooniverse.org/projects/zookeeper/galaxy-zoo/), where participants are asked to
aid classification of galaxies based on shape. This combination of remote sensing and citizen
science has proved an extremely useful initiative, and highlights the benefits to both
researchers and participants when interactive tools are both ‘user-friendly’ and informative.
Table 4 describes a selection of citizen science monitoring initiatives which focus
on/encompass kelp habitat.

This approach has the potential to expand the number of people observing and recording kelp
habitat by using members of the general public to acquire data. Recently, there has been an
expansion of citizen science around the world, using technological developments such as
mobile phone apps, evidenced by the increasing number of citizen science focused observer
projects under propagation (Silvertown, 2009; Gillett et al., 2012; Ballard et al., 2017;
Ellwood et al., 2017). The logistical difficulties of visiting kelp habitats, outlined above, are
arguably more daunting for non-experts, which can reduce the effectiveness of field based
citizen science projects for monitoring kelp resources, or put more effort in easily accessible,
well studied areas. Not all citizen science projects are field based, for example, The Floating
Forests project makes use of satellite images (Landsat) to estimate kelp distribution and
abundance (Table 4). The online training provided and computer-based method mitigates
some of the aforementioned difficulties associated with traditional surveys, although, the
feasibility of computer-based citizen science projects depends on the availability of the
resource (e.g. satellite images) that the computer project is based.

Scrutiny is often placed on the quality of citizen science data compared to data collected by
professional scientists (Cox et al., 2012; Gillett et al., 2012). Some programmes provide
training to increase data quality but volunteers can often misidentify rare species and early
alien introductions (Cox et al., 2012). Adequate training can theoretically remedy these pitfalls, but training requires extended time, labour and willingness from participants.

3.2 Harvesting

Potential impacts of wild harvesting on kelp and kelp-founded habitats have been identified (e.g. Smale et al., 2013; Steen et al., 2016), and the need for a ‘best practice’ code for harvesting recognised (Rebours et al., 2014; Mac Monagail et al., 2017). In response, the Aquaculture Stewardship Council (ASC) and the Marine Stewardship Council (MSC) are collaborating to develop a sustainable certification scheme for seaweed harvesting. The MSC-ASC Seaweed Standard became effective in March 2018 (https://improvements.msc.org/database/seaweed-standard), with an overarching aim to “contribute to the health of the world’s aquatic ecosystems” by creating a certification standard “for sustainable and socially responsible harvesting and farming practices” (MSC, 2017). To achieve this goal both baseline information and a rapid assessment technique (allowing routine monitoring of wild resources) are required to inform effective management practices.

3.3 Government data collection

Without detailed baseline knowledge of the abundance and distribution of kelp, any plans for sustainable management are compromised, and there consequently persists a need for novel monitoring efforts to inform the conservation of these ecological and socio-economically invaluable marine species. Many agencies and government bodies routinely survey inshore areas with multibeam sonar for various purposes (e.g. the UK Hydrography Office: https://www.gov.uk/government/organisations/uk-hydrographic-office and Marine Institute of Ireland: http://www.marine.ie in the northeast Atlantic and NOAA:...
https://www.ngdc.noaa.gov/ in the United States and NIWA: https://www.niwa.co.nz/ in New Zealand), and the resulting data present opportunities for modelling, mapping and monitoring of kelp resources large-scale, with dramatically reduced labour and cost.

3.4 The need for standards

Climate change, overfishing, invasive species and increased wild harvesting form a complex synergistic relationship which adversely impact kelp habitats in the northeast Atlantic. A rapid assessment technique is therefore required, to adequately and responsibly monitor, and inform the management of standing stocks. When choosing any given mapping technique there is a trade-off between spatial coverage, resolution and labour intensity (either field or desk based). The answer to a standardised remote sensing technique to quantify kelp resources may therefore lie in a combination of multiple sensors (Fig. 1). The potential application of both LiDAR and multibeam sonar information to increase kelp prediction accuracy was highlighted by Young et al. (2015), by obtaining overlapping information of coastal bathymetry (in the intertidal and offshore), the authors ensured all possible kelp habitat was included. A ‘best practice’ guide is required to standardise monitoring procedures. As aforementioned, there will always be a trade-off based on a number of factors. These range from ‘tool’ related factors i.e. spatial coverage and resolution, but also encompass budget and feasibility. A ‘one size fits all’ monitoring protocol is unrealistic, but a set of guidelines available to inform future monitoring is achievable. Table 3 and Fig. 1 presented in this review provides the frameworks needed to develop standardised procedures. Until standardised monitoring procedures are available to industry regulators, kelps will remain without a baseline from which to accurately inform management and harvesting ‘best practice’. The rapid evolution of remote sensing technologies provides new and increasingly
accurate ways to monitor kelp and other macroalgae. Tools now exist which can be used to rapidly monitor wild kelp resources evidenced by several studies cited herein, the conceptual framework presented here (Fig. 1) summarises our findings and should be used to aid the development of standardised monitoring protocols.

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Table 1. An overview of the ecological and socio-economic importance of kelp and kelp-founded habitats.

**Ecological importance**

- Kelps are habitat-formers, creating large biogenic habitats which support a wide range of associated species (~1800 species recorded in one system) (Birkett et al., 1998; Smale et al., 2013; Brodie et al., 2014; Yesson et al., 2015b). Associated flora and fauna that benefit from kelp-founded habitats include: marine mammals, crabs, sea urchins, fishes, other algae and epibiota (Mann, 1973; Teagle et al., 2017).

- Kelps are significant primary producers, both locally and for nearby habitats via direct grazing and detrital export, respectively (Reed et al., 2008; Nelson et al., 2015; Teagle et al., 2017).

- Adaptations due to turbulent water flow, associated with the sublittoral fringe of rocky shores, have allowed kelp to benefit from high levels of turbulent diffusion, permitting increased levels of primary production (Tegner and Dayton, 2000). In areas of very high and very low water motion, however, the growth rate of some Laminariales is reduced (Kregting et al., 2016). Oowed to their importance as a source of food in coastal ecosystems, kelps also play an important role in nutrient cycling through trophic transfer (Teagle et al., 2017).

- Kelp forests are noted as ‘natural barriers’ to hydraulic action, reducing the impacts of coastal erosion (Løvås and Tørum, 2001) and acting as potential flood barriers (Smale et al., 2013). Compared to other coastal habitat-formers there is comparatively limited knowledge of the extent which kelp forests provide coastal defence, particularly in the UK and Ireland, although it is likely kelp forests are providing some coastal defence at a local level (Smale et al., 2013).

**Socio-economic importance**

- Kelps are harvested worldwide (FAO, 2016; Buschmann et al., 2017; Mac Monagail et al., 2017) and kelp-founded habitats support a myriad of finfish and invertebrate fisheries globally (Tegner and Dayton, 2000; Bertocci et al., 2015; Blamey and Bolton, 2017). Many commercially important species rely on kelp-founded habitats (Tegner and Dayton, 2000), providing a nursery for Atlantic cod and European seabass (Birkett et al., 1998; Smale et al., 2013) and a feeding ground Atlantic cod and Pollack (Norderhaug et al., 2005).

- There is an increasing interest in kelp as a ‘superfood’ and for use in artisanal products, by small-scale organisations and foragers (Bouga and Combet, 2015; Mac Monagail et al., 2017). Additionally, research into the biochemical properties of macroalgae for potential uses in medicine is gaining attention (Wijesinghe and Jeon, 2012; Buschmann et al., 2017). Kelps are harvested worldwide for a variety of other uses such as biofuels, fertiliser and alginates (see Buschmann et al., 2017).

- Commercially, kelp-based ecosystems and their subsequent services are valued in their billions (€) (Beaumont et al., 2008; FAO, 2016; Blamey and Bolton, 2017). According to the FAO (2016), 27.3 million tonnes of kelp and other aquatic flora are harvested annually worldwide, with an estimated value of €4.8 billion per annum. Global production of macroalgae is increasing at a rate of ~5.7 % annually (Netalgae, 2017).

- The harvesting of macroalgae, particularly kelp, has shaped the communities and cultural identities of many coastal regions throughout the NE Atlantic (Forsythe, 2006; Guiry and Morrison, 2013; Mac Monagail et al., 2017). Although more difficult to quantify, the value of kelp-founded habitats in terms of health and well-being should also be acknowledged. Similarly, tourism supported by kelp should also not be overlooked (e.g. snorkelling, diving and recreational fishing) (Beaumont et al., 2008; Smale et al., 2013).
Table 2. A summary of several pressures affecting kelp (Laminariales, Ochrophyta).

**Climate change**

- Kelp distributions are limited by sea surface temperatures (SST) (Lüning, 1990; Yesson et al., 2015c). The northeast Atlantic has been described as a ‘hot spot for warming’ (Smale et al., 2013), which has implications for macroalgae as temperature affects growth, reproduction and overall productivity.

- Four possible outcomes have been proposed in relation to the impact of environmental change on macroalgae: i) tolerance, ii) persistence with adaptation or acclimation, iii) persistence enabled by migration, iv) extinction (Harley et al., 2012). Where pressures are too great, the likely outcome for many species will be persistence enabled by migration in the form of poleward shifts in distribution.

- Recently, several published works have reported both changes and declines in suitable habitat for kelp (Brodie et al., 2009; Bolton et al., 2012; Moy and Christie, 2012; Bush et al., 2013; Smale et al., 2013; Brodie et al., 2014; Yesson et al., 2015c; Krumhansl et al., 2016).

**Overfishing**

- The deleterious effects of overfishing of kelp-associated species on kelps (Scheffer et al., 2005; Ling et al., 2009) and other coastal ecosystems (Jackson et al., 2001), are well recognised. Kelps can be adversely impacted by overfishing of associated species through ‘top-down’ trophic cascades, due to removal of predators (particularly keystone species) (Scheffer et al., 2005).

- Linkage and dependency between kelp forests and associated species is well documented (Steneck et al. 2002); for example, hunting of sea otters in California for fur led to an increase in urchins, and a subsequent decline in kelp forest due to overgrazing (Estes and Duggins, 1995; Estes et al., 1998). This stemmed the decimation of associated biodiversity, giving rise to a barren, urchin-dominated landscape (Birkett et al., 1998).

**Invasive species**

- Introductions of invasive macroalgae to the northeast Atlantic are increasing (Sorte et al., 2010). At present, 31 species (~5 %) reported are non-natives, although this number is potentially much higher (Brodie et al., 2016), with introductions facilitated by expanding trading routes and other human movements (Mineur et al., 2008; Jueterbock et al., 2013).

- Loss (or decline) of native species provides opportunities for invasive species, sometimes assisted by the development of artificial marine structures (Brodie et al., 2014). For example, offshore renewable energy capture offers bare substrata, free of competitors, to facilitate invasion corridors across oceans, assisted by polar shipping routes, as well as through natural dispersal (Nyberg and Wallentinus, 2005).

**Wild harvesting**

- Macroalgae have been harvested in the northeast Atlantic for hundreds of years (Forsythe, 2006; Guiry and Morrison, 2013; Mac Monagail et al., 2017), but recently, under growing consumer pressure, there has been an increase in production worldwide (Buschmann et al., 2017; Chung et al., 2017; Mac Monagail, et al. 2017).

- Despite the rapid growth rate of kelps, regenerating the associated biodiverse assemblages may take considerably longer (Smale et al., 2013; Steen et al., 2016; Teagle et al., 2017). Experiments carried out in the Isle of Man and Scotland revealed some recovery of kelp biomass 3–4 years after harvesting (Birkett et al., 1998; MarineScotland, 2016), whilst studies in Norway contend that recovery can take 4-10 years when harvesting fully mature kelp (Birkett et al., 1998; Christie et al., 1998; MarineScotland, 2016; Steen et al., 2016).

- Evidence suggests that kelp forests can recover from perturbations, with most species maturing in 1–6 years, and associated communities taking 7-10 years (Steneck et al., 2002; Smale et al., 2013). The likelihood of 10 years without repeated disturbance is low, given the increase in documented stressors, both natural and anthropogenic, dependent on the biotope in question (Steneck et al., 2002).
Table 3. Remote sensing techniques currently available to monitor the distribution and abundance of Laminariales, with examples of studies which have employed the corresponding remote sensing technique to detect or monitor submerged aquatic flora.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Description</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Macroalgae</th>
<th>Macrophytes</th>
<th>author(s)</th>
</tr>
</thead>
</table>
| Satellite-borne sensors| Images of the earth collected by satellites are operated by businesses and governments (Landsat). Images can be gathered over a range of spectrums (hyper or multispectral) which can be used to identify submerged vegetation. Canopy forming kelp species such as *M. pyrifera* can be detected from satellite images in temperate regions. | • Cost effective due to great repositories of images available open source  
  • Images can cover large geographic regions  
  • Sensors can gather images over a wide range of spectrums (hyperspectral) aiding the classification of aquatic habitats | • Images gathered do not account for tides restricting transferability  
  • Success can be adversely impacted by turbidity i.e. restricted in temperate regions  
  • Images can be disrupted by atmospheric conditions  
  • Images gathered are at a relatively coarse resolution, compared to aerial imagery | Hochberg et al. (2003)  
  Andreouët et al. (2004b)  
  Dekker et al. (2005)  
  Anderson et al. (2007)  
  Vahtmae et al. (2007)  
  Cavanaugh et al. (2010)  
  Casal et al. (2011)  
  Tulldhal et al. (2013)  
  Bell et al. (2015)  
  Dekker et al. (2005)  
  Gullström et al. (2006)  
  Roessler et al. (2012) | |
| Aerial imagery          | Images collected by aircraft i.e. planes and UAVs (drones). Similar to satellite images, aerial photographs can be collected over a range of spectrums (multispectral and hyperspectral) to aid detection and classification of submerged vegetation. Coastal aerial images are available online from a number of repositories (e.g. NOAA and CCO). | • Images at finer resolutions compared to satellite images  
  • Images can be gathered in conjunction with environmental data gathered by other sensors  
  • Images can be taken over a range of spectrums (multispectral or hyperspectral) aiding classification  
  • Recent developments of UAVs is reducing costs associated with traditional aerial photography methods | • Applicable on a reduced geographic scale compared to satellite imagery  
  • Although a number of organisations provide aerial images open source, gathering images can still be expensive and time-consuming  
  • Traditional methods are expensive, although the swift evolution of drone technology is reducing associated costs | Alberotanza et al. (1999)  
  Andreouët et al. (2004a)  
  Anderson et al. (2007)  
  Nezlin et al. (2007)  
  Dierssen et al. (2015)  
  Bell et al. (2015)  
  Uhl et al. (2016)  
  Murfitt et al. (2017)  
  Pasqualini et al. (1998)  
  Dierssen et al. (2015)  
  Ventura et al. (2017) | |
| Underwater imagery      | Autonomous Underwater Vehicles (UAVs) as well as divers and drop and towed cameras from ships are capable of collecting high-resolution images of the seafloor. | • High-resolution images can be collected which can be used to accurately identify substrata, but can also be used to examine biogenic habitats and associated biota  
  • Less dependent on sea-state or tides (except in the intertidal) | • Only applicable over relatively small spatial scales  
  • Time consuming to gather and process data  
  • Expensive compared to other remote sensing techniques (in terms of coverage)  
  • Potentially hindered by turbidity and tides in the intertidal  
  • Conversion of underwater images into quantitative data difficult and slow | Smale et al. (2012)  
  Bewley et al. (2012)  
  McDonald et al. (2006) | |
<table>
<thead>
<tr>
<th><strong>LiDAR</strong></th>
<th>LiDAR uses light in the form of a pulsed laser to measure variable distances to the earth. LiDAR bathymetry and LiDAR-derived information can be used to create environmental layers to aid detection and classification of submerged vegetation. Coastal LiDAR data is available online from a number of online repositories (e.g. NOAA and CCO).</th>
</tr>
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<tr>
<td><strong>Sonar</strong></td>
<td>Sonar uses sound from an echo sounder (single or multibeam) on board a ship or other seafaring vessel to detect objects/bathymetry under the water’s surface. Bathymetric derivatives and backscatter information obtained by echo sounders can be used to produce a 3D visualisation of the seafloor. Information in the form of ‘environmental layers’ can be combined with ground-truth information to classify seabed substrate and detect submerged vegetation. A large number of governmental and non-governmental agencies have made bathymetric multibeam data freely available from several online repositories (e.g. GOV.UK, NOAA and NIWA).</td>
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<tr>
<td><strong>LiDAR</strong></td>
<td>- Large geographic expanses can be sampled quickly.</td>
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<td>- A multitude of sensors can be deployed simultaneously.</td>
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<td></td>
<td>- Information gathered is quantitative.</td>
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<td></td>
<td>- LiDAR can be restricted in temperate regions due to turbidity.</td>
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<td></td>
<td>- Tides can also effect the consistency and accuracy of classification.</td>
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<tr>
<td><strong>Sonar</strong></td>
<td>- Vast expanses of the ocean have already been mapped by governmental and non-governmental organisations and large quantities of data is available open source.</td>
</tr>
<tr>
<td></td>
<td>- Multibeam sonar can cover large geographical areas.</td>
</tr>
<tr>
<td></td>
<td>- Information gathered is quantitative.</td>
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<td></td>
<td>- Sound can travel much further underwater than light mitigating some issues raised by turbidity.</td>
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<tr>
<td></td>
<td>- Processing can be time consuming and labour intensive.</td>
</tr>
<tr>
<td></td>
<td>- Multibeam sonar is ineffective in shallow waters (&lt;2m).</td>
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<td></td>
<td>- Sonar data requires large storage capabilities.</td>
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Tulldhal et al. (2012)  
Tulldhal et al. (2013)  
Zavalas et al. (2014)  
Young et al. (2015)  
Rosso et al. (2006)  
Wang et al. (2007)  
Chust et al. (2010)  
Valle et al. (2011)  
Anderson et al. (2002)  
Kruss et al. (2008)  
Blight et al. (2011)  
McGonigle et al. (2011)  
Hasan et al. (2012)  
Rattray et al. (2013)  
Gorman et al. (2013)  
Mielck et al. (2014)  
Hasan et al. (2014)  
Young et al. (2015)  
Pasqualini et al. (1998)  
Hermand et al. (2004)  
De Falco et al. (2010)  
Micallef et al. (2012)
### Online repositories

<table>
<thead>
<tr>
<th>Repository</th>
<th>Description</th>
<th>Website</th>
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<tbody>
<tr>
<td>AlgaeBase</td>
<td>AlgaeBase is a species inventory database with country-level distribution data which includes terrestrial, marine and freshwater organisms.</td>
<td><a href="http://www.algaebase.org">www.algaebase.org</a></td>
</tr>
<tr>
<td>Ocean Biogeographic Information System (OBIS)</td>
<td>Repository gateway to the world’s ocean biodiversity and biogeographic data (i.e. museum catalogues and survey records).</td>
<td><a href="http://iobis.org/">http://iobis.org/</a></td>
</tr>
<tr>
<td>Temperate Reef Base</td>
<td>Temperate Reef Base is a resource for temperate reef researchers worldwide to use and contribute a variety of kelp related data. Originally established in collaboration with the Kelp Ecology Ecosystem Network (KEEN).</td>
<td><a href="http://temperatereefbase.im.as.utas.edu.au/static/landing.html">http://temperatereefbase.im.as.utas.edu.au/static/landing.html</a></td>
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### Citizen science projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Description</th>
<th>Website</th>
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<tr>
<td>Nature Watch</td>
<td>In New Zealand, the National Institute of Water and Atmospheric Research (NIWA) has established the citizen science project; Nature Watch, within which they are encouraging volunteers to photograph and document large brown seaweeds in an attempt to assess environmental change.</td>
<td><a href="http://naturewatch.org.nz/">http://naturewatch.org.nz/</a></td>
</tr>
<tr>
<td>The Big Seaweed Search</td>
<td>A collaborative effort between the Natural History Museum (NHM) and Marine Conservation Society (MCS). The project aims to identify and record seaweed species through-out the British Isles. Occurrence records are submitted to the NBN Gateway for open source use.</td>
<td><a href="http://www.nhm.ac.uk/take-part/citizen-science/big-seaweed-search.html">http://www.nhm.ac.uk/take-part/citizen-science/big-seaweed-search.html</a></td>
</tr>
<tr>
<td>Capturing Our Coast</td>
<td>By providing training at several institutions prior to surveying, Capturing Our Coast aims to collect a wide range ecological data of the UK coast, including macroalgae.</td>
<td><a href="http://www.capturingourcoast.co.uk/">www.capturingourcoast.co.uk/</a></td>
</tr>
<tr>
<td>Atlas of Life</td>
<td>Atlas of Life is a citizen science initiative focused on a particular region in southeast Australia. The initiative encourages volunteers to record and log sightings in their online repository: NatureMapr.</td>
<td><a href="https://www.atlasoflife.org.au/">https://www.atlasoflife.org.au/</a></td>
</tr>
<tr>
<td>Floating Forests</td>
<td>Floating Forests is a citizen science initiative to study global distributions of <em>Macrocystis pyrifera</em> over a long-term period between 1984 to the present, where the public identify and label satellite images containing kelp.</td>
<td><a href="https://www.zooniverse.org/projects/zooniverse/floating-forests">https://www.zooniverse.org/projects/zooniverse/floating-forests</a></td>
</tr>
<tr>
<td>MarClim Project</td>
<td>The MarClim project, run by the Marine Biological Association was set up to investigate how climate change affected marine organisms in the UK. Annual surveys of 100s of sites are carried out in a bid to detect shifts in species biogeographic distributions.</td>
<td><a href="http://www.mba.ac.uk/marclim/">www.mba.ac.uk/marclim/</a></td>
</tr>
</tbody>
</table>
Fig. 1. ‘Remote sensing of macroalgae decision tree’ provided to aid the selection of appropriate remote sensing tools for mapping submerged and intertidal macroalgae. The detection of submerged algae will likely be best achieved using a combination of acoustic and optical techniques as acoustic sensors are ineffective in water <2 m.