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

Matthew Bennion[1, 2], Jessica Fisher[3], Chris Yesson[1, 2], Juliet Brodie[2]

1. Institute of Zoology, Zoological Society of London, Regent's Park, London, NW1 4RY, United Kingdom

2. Natural History Museum, Department of Life Sciences, Cromwell Road, London, SW7 5BD, United Kingdom

3. Durrell Institute of Conservation and Ecology, School of Anthropology and Conservation, University of Kent, Canterbury, Kent, United Kingdom

Corresponding author: Matthew Bennion. E-mail: matthewbennion93@gmail.com

ORCID ID

Matthew Bennion: 0000-0001-7559-4534

Jess Fisher: 0000-0002-1435-9247

Chris Yesson: 0000-0002-6731-4229

Juliet Brodie: 0000-0001-7622-2564

Email

Matthew Bennion: matthewbennion93@gmail.com

Jess Fisher: jcf22@kent.ac.uk

Chris Yesson: chris.yesson@ioz.ac.uk

Juliet Brodie: j.brodie@nhm.ac.uk

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 distributions (Yesson et al., 2015b). 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 (Humborstad 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.

Conflict of interest - All authors declare they have no conflict of interest.

Acknowledgements

The authors would like to express their thanks to The Crown Estate for funding this study.

References

Alberotanza, L. Hyperspectral aerial images. A valuable tool for submerged vegetation recognition in the Orbetello Lagoons, Italy. Int J Remote Sens 20:523-533 (1999).

Anderson, J. T., R. S. Gregory, W. T. Collins. Acoustic classification of marine habitats in coastal Newfoundland. ICES J Mar Sci 59:156-167 (2002).

Anderson, J. T., D. Van Holliday, R. Kloser, D. G. Reid, Y. Simard. Acoustic seabed classification: current practice and future directions. ICES J Mar Sci 65:1004-1011 (2008).

Anderson, R. J., A. Rand, M. D. Rothman, A. Share, J. J. Bolton. Mapping and quantifying the South African kelp resource. Afr J Mar Sci 29:369-378 (2007).

Andréfouët, S., C. Payri, E. J. Hochberg, C. Hu, M. J. Atkinson, F. E. Muller-Karger. Use of in situ and airborne reflectance for scaling-up spectral discrimination of coral reef macroalgae from species to communities. Mar Ecol Prog Ser 283:161-177 (2004a).

Andréfouët, S., M. Zubia, C. Payri. Mapping and biomass estimation of the invasive brown algae *Turbinaria ornata* (Turner) J. Agardh and *Sargassum mangarevense* (Grunow) Setchell on heterogeneous Tahitian coral reefs using 4-meter resolution IKONOS satellite data. Coral Reefs 23:26-38 (2004b).

Ballard, H. L., L. D. Robinson, A. N. Young, G. B. Pauly, L. M. Higgins, R. F. Johnson, J. C. Tweddle. Contributions to conservation outcomes by natural history museum-led citizen science: examining evidence and next steps. Biol Conserv 208:87-97 (2017).

Barrett, E. C., L. F. Curtis. Introduction to Environmental Remote Sensing. Chapman and Hall (1976).

Bartsch, I., C. Wiencke, K. Bischof, C. M. Buchholz, B. H. Buck, A. Eggert, P. Feuerpfeil, D. Hanelt, S. Jacobsen, R. Karez, U. Karsten, M. Molis, M. Y. Roleda, H. Schubert, R. Schumann, K. Valentin, F. Weinberger, J. Wiese. The genus *Laminaria sensu lato*: recent insights and developmentsThe genus Laminaria sensu lato: recent insights and developments. Eur J Phycol 43:1-86 (2008).

Beaumont, N. J., M. C. Austen, S. C. Mangi, M. Townsend. Economic valuation for the conservation of marine biodiversity. Mar Pollut Bull 56:386-396 (2008).

Bell, T. Quantifying intertidal macroalgae abundance using aerial photography on the Isle of Wight. MSc Thesis. Imperial College London (2015).

Bell, T. W., K. C. Cavanaugh, D. A. Siegel. Remote monitoring of giant kelp biomass and physiological condition: An evaluation of the potential for the Hyperspectral Infrared Imager (HyspIRI) mission. Remote Sens Environ 167:218-228 (2015).

Bendell, L. I., P. C. Y. Wan. Application of aerial photography in combination with GIS for coastal management at small spatial scales: a case study of shellfish aquaculture. J Coast Conserv 15:417-431 (2011).

Bertocci, I., R. Araújo, P. Oliveira, I. Sousa‐Pinto. Potential effects of kelp species on local fisheries. J Appl Ecol 52:1216-1226 (2015).

Bewley, M., B. Douillard, N. Nourani-Vatani, A. Friedman, O. Pizarro, S. Williams. Automated species detection: An experimental approach to kelp detection from sea-floor AUV images. Proceedings of the Australasian Conference on Robotics and Automation, Australia (2012).

Bicknell, A., B. Godley, E. Sheehan, S. Votier, M. Witt. Camera technology for monitoring marine biodiversity and human impact. Front Ecol Environ 14:424-432 (2016).

Birkett, D. A., C. A. Maggs, M. J. Dring, P. J. S. Boaden, R. Seed. Infralittoral Reef Biotopes with Kelp Species (volume VII). An overview of dynamic and sensitivity characteristics for conservation management of marine SACs. Scottish Association of Marine Science (UK Marine SACs Project) (1998).

Blamey, L. K., J. J. Bolton. The economic value of South African kelp forests and temperate reefs: Past, present and future. J Mar Syst (2017).

Blight, A., R. Foster-Smith, I. Sotheran, J. Egerton, R. McAllen, G. Savidge. Development of a methodology for the quantitative assessment of Ireland’s inshore Kelp resource. Marine Institute (2011).

Bolton, J. J., R. J. Anderson, A. J. Smit, M. D. Rothman. South African kelp moving eastwards: the discovery of *Ecklonia maxima* (Osbeck) Papenfuss at De Hoop Nature Reserve on the south coast of South Africa. Afr J Mar Sci 34:147-151 (2012).

Bouga, M., E. Combet. Emergency of seaweed and seaweed-containing food in the UK: Focus on labelling, iodine content, toxicity and nutrition. Foods 4:240-253 (2015).

Brock, J. C., C. W. Wright, T. D. Clayton, A. Nayegandhi. LIDAR optical rugosity of coral reefs in Biscayne National Park, Florida. Coral Reefs 23:48-59 (2004).

Brodie, J., R. A. Andersen, M. Kawachi, A. J. K. Millar. Endangered algal species and how to protect them. Phycologia 48:423-438 (2009).

Brodie, J., L. Ash, I. Tittley, C. Yesson. A comparison of high resolution aerial imagery and satellite imagery in differentiation and abundance assessment of seaweed communities. Manuscript submitted for publication (2018).

Brodie, J., J. Wilbraham, J. Pottas, M. D. Guiry. A revised check-list of the seaweeds of Britain. J Mar Biol Assoc UK 96:1005-1029 (2016).

Brodie, J., C. J. Williamson, D. A. Smale, N. A. Kamenos, N. Mieszkowska, R. Santos, M. Cunliffe, M. Steinke, C. Yesson, K. M. Anderson, V. Asnaghi, C. Brownlee, H. L. Burdett, M. T. Burrows, S. Collins, P. J. C. Donohue, B. Harvey, A. Foggo, F. Noisette, J. Nunes, F. Ragazzola, J. A. Raven, D. N. Schmidt, D. Suggett, M. Teichberg, J. M. Hall-Spencer. The future of the northeast Atlantic benthic flora in a high CO2 world. Ecol Evol 4:2787-2798 (2014).

Brown, C. J., P. Blondel. Developments in the application of multibeam sonar backscatter for seafloor habitat mapping. Appl Acoust 70:1242-1247 (2009).

Brown, C.J., A. Mitchell, D. S. Limpenny, M. R. Robertson, M. Service, N. Golding. Mapping seabed habitats in the Firth of Lorn off the west coast of Scotland: evaluation and comparison of habitat maps produced using the acoustic ground-discrimination system, RoxAnn, and sidescan sonar. ICES J Mar Sci 62:790-802 (2005).

Brown, C. J., S. J. Smith, P. Lawton, J. T. Anderson. Benthic habitat mapping: a review of progress towards improved understanding of the spatial ecology of the seafloor using acoustic techniques. Estuar Coast Shelf Sci 92:502-520 (2011).

Buschmann, A. H., C. Camus, J. Infante, A. Neori, Á. Israel, M. C. Hernández-González, S. V. Pereda, J. L. Gomez-Pinchetti, A. Golberg, N. Tadmor-Shalev. Seaweed production: overview of the global state of exploitation, farming and emerging research activity. Eur J Phycol 52:391-406 (2017).

Bush, L., A. Davis, C. A. Maggs, C. Yesson, J. A. Brodie. Review of evidence for the loss of large brown macroalgae . A Review For The Crown Estate. London, UK (2013).

Casal, G., N. Sanchez-Carnero, E. Sanchez-Rodriguez, J. Freire. Remote sensing with SPOT-4 for mapping kelp forests in turbid waters on the south European Atlantic shelf. Estuar Coast Shelf Sci 91:371-378 (2011).

Casella, E., A. Collin, D. Harris, S. Ferse, S. Bejarano, V. Parravicini, J. L. Hench, A. Rovere. Mapping coral reefs using consumer-grade drones and structure from motion photogrammetry techniques. Coral Reefs 36:269-275 (2017).

Cavanaugh, K. C., D. A. Siegel, B. P. Kinlan, D. C. Reed. Scaling giant kelp field measurements to regional scales using satellite observations. Mar Ecol Prog Ser 403:13-27 (2010).

Chen, P., S. C. Liew, R. Lim, K. L. Kwoh. Mapping coastal ecosystems of an offshore landfill island using WorldView-2 high resolution satellite imagery Proceedings of the 34th International Symposium on Remote Sensing of Environment, Sydney, Australia (2011).

Christie, H., S. Fredriksen, E. Rinde. Regrowth of kelp and colonization of epiphyte and fauna community after kelp trawling at the coast of Norway Recruitment, Colonization and Physical-Chemical Forcing in Marine Biological Systems. Springer, pp 49-58 (1998).

Chung, I. K., C. F. A. Sondak, J. Beardall. The future of seaweed aquaculture in a rapidly changing world. Eur J Phycol 52:495-505 (2017).

Chust, G., M. Grande, I. Galparsoro, A. Uriarte, Á. Borja. Capabilities of the bathymetric Hawk Eye LiDAR for coastal habitat mapping: a case study within a Basque estuary. Estuar Coast Shelf Sci 89:200-213 (2010).

Connell, S. D., B. D. Russell, D. J. Turner, S. A. Shepherd, T. Kildea, D. Miller, L. Airoldi, A. Cheshire. Recovering a lost baseline: missing kelp forests from a metropolitan coast. Mar Ecol Prog Ser 360:63-72 (2008).

Cord, A.F., Meentemeyer, R.K., Leitão, P.J. and Václavík, T., 2013. Modelling species distributions with remote sensing data: bridging disciplinary perspectives. J Biogeog 40:2226-2227 (2013).

Cox, T. E., J. Philippoff, E. Baumgartner, C. M. Smith. Expert variability provides perspective on the strengths and weaknesses of citizen - driven intertidal monitoring program. Ecol Appl 22:1201-1212 (2012).

Dayton, P. K.. Ecology of kelp communities. Annu Rev Ecol Evol Syst 16:215-245 (1985).

De Clippele, L. H., J. Gafeira, K. Robert, S. Hennige, M. S. Lavaleye, G. C. A. Duineveld, V. A. I. Huvenne, J. M. Roberts. Using novel acoustic and visual mapping tools to predict the small-scale spatial distribution of live biogenic reef framework in cold-water coral habitats. Coral Reefs 36:255-268 (2017).

De Falco, G., R. Tonielli, G. Di Martino, S. Innangi, S. Simeone, I. M. Parnum. Relationships between multibeam backscatter, sediment grain size and *Posidonia oceanica* seagrass distribution. Cont Shelf Res 30:1941-1950 (2010).

Dekker, A. G., V. E. Brando, J. M. Anstee. Retrospective seagrass change detection in a shallow coastal tidal Australian lake. Remote Sens Environ 97:415-433 (2005).

Dierssen, H. M., A. Chlus, B. Russell. Hyperspectral discrimination of floating mats of seagrass wrack and the macroalgae *Sargassum* in coastal waters of Greater Florida Bay using airborne remote sensing. Remote Sens Environ 167:247-258 (2015).

Downie, A. J., D. W. Donnan, A. J. Davison. A review of Scottish Natural Heritage's work in subtidal marine biotope mapping using remote sensing. Int J Remote Sens 20:585-592 (1999).

Ehrhold, A., D. Hamon, B. Guillaumont. The REBENT monitoring network, a spatially integrated, acoustic approach to surveying nearshore microbenthic habitats: application to the Bay of Concarneau (South Brittany, France). ICES J Mar Sci 63:1604-1615 (2006).

Elith, J., J. R. Leathwick. Species distribution models: ecological explanation and prediction across space and time. Annu Rev Ecol Syst 40:677-697 (2009).

Ellwood, E. R., T. M. Crimmins, A. J. Miller-Rushing. Citizen science and conservation: Recommendations for a rapidly moving field. Biol Conserv 208:1-4 (2017).

Estes, J. A., D. O. Duggins. Sea otters and kelp forests in Alaska: generality and variation in a community ecological paradigm. Ecol Monogr 65:75-100 (1995).

Estes, J. A., M. T. Tinker, T. M. Williams, D. F. Doak. Killer Whale Predation on Sea Otters Linking Oceanic and Nearshore Ecosystems. Science 282:473-476 (1998).

FAO. The State of the World Fisheries and Aquaculture 2016 Contributing to food security and nutrition for all, Rome, pp 200 (2016).

Ferguson, R. L., K. Korfmacher. Remote sensing and GIS analysis of seagrass meadows in North Carolina, USA. Aquat Bot 58:241-258 (1997).

Ferguson, R. L., L. L. Wood, D. B. Graham. Monitoring spatial change in seagrass habitat with aerial photography. Photogramm Eng Remote Sensing 59:1033-1038 (1993).

Forsythe, W. The archaeology of the kelp industry in the northern islands of Ireland. INJA 35:218-229 (2006).

Fyfe, S.K. Spatial and temporal variation in spectral reflectance: Are seagrass species spectrally distinct? Limnol Oceanogr 48:464-479 (2003).

Gillett, D.J, D. J. Pondella, J. Freiwald, K. C. Schiff, J. E. Caselle, C. Shuman, S. B. Weisberg. Comparing volunteer and professionally collected monitoring data from the rocky subtidal reefs of Southern California, USA. Environ Monit Assess 184:3239-3257 (2012).

Gorman, D., T. Bajjouk, J. Populus, M. Vasquez, A. Ehrhold. Modeling kelp forest distribution and biomass along temperate rocky coastlines. Mar Biol 160:309-325 (2013).

Guiry, M. D., L. Morrison. The sustainable harvesting of *Ascophyllum nodosum* (Fucaceae, Phaeophyceae) in Ireland, with notes on the collection and use of some other brown algae. J Appl Phycol 25:1823-1830 (2013).

Gullström, M., B. Lundén, M. Bodin, J. Kangwe, M. C. Öhman, M. S. P. Mtolera, M. Björk. Assessment of changes in the seagrass-dominated submerged vegetation of tropical Chwaka Bay (Zanzibar) using satellite remote sensing. Estuar Coast Shelf Sci 67:399-408 (2006).

Harley, C. D. G., K. M. Anderson, K. W. Demes, J. P. Jorve, R. L. Kordas, T. A. Coyle, M. H. Graham. Effects of climate change on global seaweed communities. J Phycol 48:1064-1078 (2012).

Hasan, R. C., D. Ierodiaconou, L. Laurenson. Combining angular response classification and backscatter imagery segmentation for benthic biological habitat mapping. Estuar Coast Shelf Sci 97:1-9 (2012).

Hasan, R. C., D. Ierodiaconou, L. Laurenson, A. Schimel. Integrating multibeam backscatter angular response, mosaic and bathymetry data for benthic habitat mapping. Plos one 9:e97339 (2014).

Hermand, J-P., L. Seuront, P. G. Strutton. Acoustic remote sensing of photosynthetic activity in seagrass beds in Scaling Methods in Aquatic Ecology. Measurement Analysis Simulation, Boca Raton, Florida:CRC Press LLC pp. 65-96 (2004).

Hochberg, E. J., M. J. Atkinson. Capabilities of remote sensors to classify coral, algae, and sand as pure and mixed spectra. Remote Sens Environ 85:174-189 (2003).

Hodgson, A., N. Kelly, D. Peel. Unmanned aerial vehicles (UAVs) for surveying marine fauna: a dugong case study. PloS one 8:e79556 (2013).

Holman, R., M. C. Haller. Remote sensing of the nearshore. Review of Marine Science 5:95-113 (2013).

Holmes, R. Developing spatially transferable models of intertidal macroalgae distribution using false colour infrared aerial photography and support vector machine supervised classification. MSc Thesis. University College London (2015).

Humborstad, O. B., L. Nottestad, S. Lokkeborg, H. T. Rapp. RoxAnn bottom classification system, sidescan sonar and video-sledge: spatial resolution and their use in assessing trawling impacts. ICES J Mar Sci 61:53-63 (2004).

Jackson, J. B. C., M. X. Kirby, W. H. Berger, K. A. Bjorndal, L. W. Botsford, B. J. Bourque, R. H. Bradbury, R. Cooke, J. Erlandson, J. A. Estes, T. P. Hughes, S. Kidwell, C. B. Lange, H. S. Lenihan, J. M. Pandolfi, C. H. Peterson, R. S. Steneck, M. J. Tegner, R. R. Warner. Historical Overfishing and the Recent Collapse of Coastal Ecosystems. Science 293:629-637 (2001).

Jones, A. T., J. Greinert, D. A. Bowden, I. Klaucke, C. J. Petersen, G. L. Netzeband, W. Weinrebe. Acoustic and visual characterisation of methane-rich seabed seeps at Omakere Ridge on the Hikurangi Margin, New Zealand. Mar Geol 272:154-169 (2010).

Jueterbock, A., L. Tyberghein, H. Verbruggen, J. A. Coyer, J. L. Olsen, G. Hoarau. Climate change impact on seaweed meadow distribution in the North Atlantic rocky intertidal. Ecol Evol 3:1356-1373 (2013).

Klemas, V. V. Coastal and Environmental Remote Sensing from Unmanned Aerial Vehicles: An Overview. J Coastal Res 31:1260-1267 (2015).

Komatsu, T., C. Igarashi, K. Tatsukawa, S. Sultana, Y. Matsuoka, S. Harada. Use of multi-beam sonar to map seagrass beds in Otsuchi Bay on the Sanriku Coast of Japan. Aquat Living Resour 16:223-230 (2003).

Kregting, L., A. J. Blight, B. Elsäßer. and G. Savidge. The influence of water motion on the growth rate of the kelp *Laminaria digitata*. J Exp Mar Bio Ecol 478:86-95 (2016).

Krumhansl, K. A., D. K. Okamoto, A. Rassweiler, M. Novak, J. J. Bolton, K. C. Cavanaugh, S. D. Connell, C. R. Johnson, B. Konar, S. D. Ling. Global patterns of kelp forest change over the past half-century. Proceedings of the National Academy of Sciences 113:13785-13790 (2016).

Kruss, A., P. Blondel, J. Tegowski, J. Wiktor, A. Tatarek. Estimation of macrophytes using single-beam and multibeam echosounding for environmental monitoring of Arctic fjords (Kongsfjord, West Svalbard Island). J Acoust Soc Am 123:3213-3213 (2008).

Lefsky, M. A., W. B. Cohen, G. G. Parker, D. J. Harding. Lidar remote sensing for ecosystem studies: Lidar, an emerging remote sensing technology that directly measures the three-dimensional distribution of plant canopies, can accurately estimate vegetation structural attributes and should be of particular interest to forest, landscape, and global ecologists. AIBS Bulletin 52:19-30 (2002).

Ling, S. D., C. R. Johnson, S. D. Frusher, K. R. Ridgway. Overfishing reduces resilience of kelp beds to climate-driven catastrophic phase shift. Proceedings of the National Academy of Sciences of the United States of America 106:22341-22345 (2009).

Løvås, S. M., A. Tørum. Effect of the kelp *Laminaria hyperborea* upon sand dune erosion and water particle velocities. Coastal Engineering 44: 37-63 (2001).

Lüning, K. Seaweeds: their environment, biogeography, and ecophysiology. John Wiley & Sons (1990).

Mac Monagail, M., L. Cornish, L. Morrison, R. Araújo, A. T. Critchley. Sustainable harvesting of wild seaweed resources. Eur J Phycol 52:371-390 (2017).

Mann, K. H. Seaweeds: Their Productivity and Strategy for Growth. Science 182:975-981 (1973).

Marine Scotland. Wild Seaweed Harvesting: Strategic Environmental Assessment - Environmental Report. In: Marine&Fisheries (ed). Scottish Government, Scotland (2016).

McDonald, J. I., G. T. Coupland, G. A. Kendrick. Underwater video as a monitoring tool to detect change in seagrass cover. J Environ Manage 80:148-155 (2006).

McGonigle, C., J. H. Grabowski, C. J. Brown, T. C. Weber, R. Quinn. Detection of deep water benthic macroalgae using image-based classification techniques on multibeam backscatter at Cashes Ledge, Gulf of Maine, USA. Estuar Coast Shelf Sci 91:87-101 (2011).

Meleder, V., J. Populus, B. Guillaumont, T. Perrot, P. Mouquet. Predictive modelling of seabed habitats: case study of subtidal kelp forests on the coast of Brittany, France. Mar Biol 157:1525-1541 (2010).

Micallef, A., T. P. Le Bas, V. A. I. Huvenne, P. Blondel, V. Hühnerbach, A. Deidun. A multi-method approach for benthic habitat mapping of shallow coastal areas with high-resolution multibeam data. Cont Shelf Res 39:14-26 (2012).

Mielck, F., I. Bartsch, H. C. Hass, A. C. Wölfl, D. Bürk, C. Betzler. Predicting spatial kelp abundance in shallow coastal waters using the acoustic ground discrimination system RoxAnn. Estuar Coast Shelf Sci 143:1-11 (2014).

Mineur, F., M. P. Johnson, C. A. Maggs. Macroalgal introductions by hull fouling on recreational vessels: seaweeds and sailors. Environ Manage 42:667-676 (2008).

Moy, F. E., H. Christie. Large-scale shift from sugar kelp (*Saccharina latissima*) to ephemeral algae along the south and west coast of NorwayLarge-scale shift from sugar kelp (*Saccharina latissima*) to ephemeral algae along the south and west coast of Norway. Mar Biol Res 8:309-321 (2012).

MSC. Marine Stewardship Council Program Improvements Marine Stewardship Council. Retrieved from: https://improvements.msc.org/database/seaweed-standard. Accessed: 5 Sept 2017 (2017).

Murfitt, S. L., B. M. Allan, A. Bellgrove, A. Rattray, M. A. Young, D. Ierodiaconou. Applications of unmanned aerial vehicles in intertidal reef monitoring. Sci Rep 7:10259 (2017).

Nelson, W., K. Neill, R. D'Archino, T. Anderson, J. Beaumont, J. Dalen. Beyond diving depths: deepwater macroalgae in the New Zealand region. Mar Biodivers 45:797-818 (2015).

Netalgae. Netalgae Project and Network. Retrieved from: www.netalgae.eu. Accessed: 20 Sept 2017 (2017).

Newbold, T. Applications and limitations of museum data for conservation and ecology, with particular attention to species distribution models. Prog Phys Geogr 34:3-22 (2010).

Newman, G., Wiggins, A., Crall, A., Graham, E., Newman, S. and Crowston, K. The future of citizen science: emerging technologies and shifting paradigms. Front Ecol Environ 10:298-304 (2012).

Nezlin, N. P., K. Kamer, E. D. Stein. Application of color infrared aerial photography to assess macroalgal distribution in an eutrophic estuary, upper Newport Bay, California. Estuar Coast 30:855-868 (2007).

Norderhaug, K. N., H. Christie, J. H. Fossa, S. Fredriksen. Fish-macrofauna interactions in a kelp (*Laminaria hyperborea*) forest. J Mar Biol Assoc UK 85:1279-1286 (2005).

Norris, J. G., S. Wyllie-Echeverria, T. Mumford, A. Bailey, T. Turner. Estimating basal area coverage of subtidal seagrass beds using underwater videography. Aquat Bot 58:269-287 (1997).

Nyberg, C. D., I. Wallentinus. Can species traits be used to predict marine macroalgal introductions? Biol Invasions 7:265-279 (2005).

Pailhas, Y., Y. Petillot, C. Capus. High-resolution sonars: what resolution do we need for target recognition? EURASIP J Adv Signal Process 2010: 205095 (2010).

Pan, Z. G., C. Glennie, J. C. Fernandez-Diaz, M. Starek. Comparison of bathymetry and seagrass mapping with hyperspectral imagery and airborne bathymetric lidar in a shallow estuarine environment. Int J Remote Sens 37:516-536 (2016).

Pasqualini, V., C. Pergent-Martini, P. Clabaut, G. Pergent. Mapping of *Posidonia oceanica* using Aerial Photographs and Side Scan Sonar: Application off the Island of Corsica (France). Estuar Coast Shelf Sci 47:359-367 (1998).

Pauly, K., O. De Clerck. GIS-based environmental analysis, remote sensing, and niche modelling of seaweed communities, in: Seaweeds and their Role in Globally Changing Environments. Cellular Origin, Life in Extreme Habitats and Astrobiology. Springer, Netherlands, pp 93-114 (2010).

Pergent, G., B. Monnier, P. Clabaut, G. Gascon, C. Pergent-Martini, A. Valette. Innovative method for optimizing side-scan sonar mapping: The blind band unveiled. Estuar Coast Shelf Sci 194:77-83 (2017).

Proosdij, A. S. J., M. S. M. Sosef, J. J. Wieringa, N. Raes. Minimum required number of specimen records to develop accurate species distribution models. Ecography 39:542-552 (2016).

Rattray, A., D. Ierodiaconou, J. Monk, V. L. Versace, L. J. B. Laurenson. Detecting patterns of change in benthic habitats by acoustic remote sensing. Mar Ecol Prog Ser 477:1-13 (2013).

Rebours, C., E. Marinho-Soriano, J. A. Zertuche-González, L. Hayashi, J. A. Vásquez, P. Kradolfer, G. Soriano, R. Ugarte, M. H. Abreu, I. Bay-Larsen. Seaweeds: an opportunity for wealth and sustainable livelihood for coastal communities. J Appl Phycol 26: 1939-1951 (2014).

Reed, D. C., A. Rassweiler, K. K. Arkema. Biomass rather than growth rate determines variation in net primary production by giant kelp. Ecology 89:2493-2505 (2008).

Roessler, S., P. Wolf, T. Schneider, A. Melzer. Monitoring of invasive aquatic plants using multitemporal RapidEye-data, pp 23-25 (2012).

Rosso, P. H., S. L. Ustin, A. Hastings. Use of lidar to study changes associated with *Spartina* invasion in San Francisco Bay marshes. Remote Sens Environ 100:295-306 (2006).

Šaškov, A., T. G. Dahlgren, Y. Rzhanov, M-L. Schläppy. Comparison of manual and semi-automatic underwater imagery analyses for monitoring of benthic hard-bottom organisms at offshore renewable energy installations. Hydrobiologia 756:139-153 (2015).

Scheffer, M., S. Carpenter, B. de Young. Cascading effects of overfishing marine systems. Trends Ecol Evol 20:579-581 (2005).

Silva, T. S. F., M. P. F. Costa, J. M. Melack, E. Novo. Remote sensing of aquatic vegetation: theory and applications. Environ Monit Assess 140:131-145 (2008).

Silvertown J. A new dawn for citizen science. Trends Ecol Evol 24:467-471 (2009).

Singh, H., A. Can, R. Eustice, S. Lerner, N. McPhee, C. Roman. Seabed AUV offers new platform for high‐resolution imaging. Eos, Transactions American Geophysical Union 85:289-296 (2004).

Smale, D. A., M. T. Burrows, P. Moore, N. O'Connor, S. J. Hawkins. Threats and knowledge gaps for ecosystem services provided by kelp forests: a northeast Atlantic perspective. Ecol Evol 3:4016-4038 (2013).

Smale, D. A., G. A. Kendrick, E. S. Harvey, T. J. Langlois, R. K. Hovey, K. P. Van Niel, K. I. Waddington, L. M. Bellchambers, M. B. Pember, R. C. Babcock, M. A. Vanderklift, D. P. Thomson, M. V. Jakuba, O. Pizarro, S. B. Williams. Regional-scale benthic monitoring for ecosystem-based fisheries management (EBFM) using an autonomous underwater vehicle (AUV). ICES J Mar Sci 69:1108-1118 (2012).

Smale, D. A., P. J. Moore. Variability in kelp forest structure along a latitudinal gradient in ocean temperature. J Exp Mar Bio Ecol 486:255-264 (2017).

Sorte, C. J. B, S. L. Williams, R. A. Zerebecki. Ocean warming increases threat of invasive species in a marine fouling community. Ecology 91:2198-2204 (2010).

Steen, H., F. E. Moy, T. Bodvin, V. Husa. Regrowth after kelp harvesting in Nord-Trøndelag, Norway. ICES J Mar Sci 73:2708-2720 (2016).

Stekoll, M. S., L. E. Deysher, M. Hess. A remote sensing approach to estimating harvestable kelp biomass. J Appl Phycol 18:323-334 (2006).

Steneck, R. S., M. H. Graham, B. J. Bourque, D. Corbett, J. M. Erlandson, J. A. Estes, M. J. Tegner. Kelp forest ecosystems: biodiversity, stability, resilience and future. Environ Conserv 29:436-459 (2002).

Strong, J. A., M. Elliott. The value of remote sensing techniques in supporting effective extrapolation across multiple marine spatial scales. Mar Pollut Bull 116:405-419 (2017).

Teagle, H., S. J. Hawkins, P. J. Moore, D. A. Smale. The role of kelp species as biogenic habitat formers in coastal marine ecosystems. J Exp Mar Bio Ecol 492:81-98 (2017).

Tegner, M. J., P. K. Dayton. Ecosystem effects of fishing in kelp forest communities. ICES J Mar Sci 57:579-589 (2000).

Tulldahl, H. M., P. Philipson, H. Kautsky, S. A. Wikström. Sea floor classification with satellite data and airborne lidar bathymetry. Proceedings of SPIE 8724:87240B-1 (2013).

Tulldahl, H. M., S. A. Wikstrom. Classification of aquatic macrovegetation and substrates with airborne lidar. Remote Sens Environ 121:347-357 (2012).

Uhl, F., I. Bartsch, N. Oppelt. Submerged Kelp Detection with Hyperspectral Data. Remote Sens 8:487 (2016).

Vahtmäe, E., T. Kutser. Mapping bottom type and water depth in shallow coastal waters with satellite remote sensing. J Coastal Res 50:185-189 (2007).

Valle, M., Á Borja, G. Chust, I. Galparsoro, J. M. Garmendia. Modelling suitable estuarine habitats for *Zostera noltii*, using ecological niche factor analysis and bathymetric LiDAR. Estuar Coast Shelf Sci 94:144-154 (2011).

van Rein, H., C. J. Brown, R. Quinn, J. Breen, D. Schoeman. An evaluation of acoustic seabed classification techniques for marine biotope monitoring over broad-scales (>1 km2) and meso-scales (10 m2–1 km2). Estuar Coast Shelf Sci 93:336-349 (2011).

Ventura, D., A. Bonifazi, M. F. Gravina, G. D. Ardizzone. Unmanned Aerial Systems (UASs) for Environmental Monitoring: A Review with Applications in Coastal Habitats Aerial Robots-Aerodynamics, Control and Applications. InTech (2017).

Ventura, D., M. Bruno, G. J. Lasinio, A. Belluscio, G. Ardizzone. A low-cost drone based application for identifying and mapping of coastal fish nursery grounds. Estuar Coast Shelf Sci 171:85-98 (2016).

Vergés, A., C. Doropoulos, H. A. Malcolm, M. Skye, M. Garcia-Pizá, E. M. Marzinelli, A. H. Campbell, E. Ballesteros, A. S. Hoey, A. Vila-Concejo. Long-term empirical evidence of ocean warming leading to tropicalization of fish communities, increased herbivory, and loss of kelp. Proceedings of the National Academy of Sciences: 201610725 (2016).

Wang, C-K., W. D. Philpot. Using airborne bathymetric lidar to detect bottom type variation in shallow waters. Remote Sens Environ 106:123-135 (2007).

Wannasiri, W., M. Nagai, K. Honda, P. Santitamnont, P. Miphokasap. Extraction of Mangrove Biophysical Parameters Using Airborne LiDAR. Remote Sens 5:1787-1808 (2013).

Wijesinghe, W., Y. J. Jeon. Biological activities and potential industrial applications of fucose rich sulfated polysaccharides and fucoidans isolated from brown seaweeds: A review. Carbohydr Polym 88:13-20 (2012).

Yesson, C., L. Ash, J. Brodie. Using aerial images to quantify the extent of coastal seaweed habitats. A Review For The Crown Estate. London, UK (2015a).

Yesson, C., L. E. Bush, A. J. Davies, C. A. Maggs, J. Brodie. The distribution and environmental requirements of large brown seaweeds in the British Isles. J Mar Biol Assoc UK 95:669-680 (2015b).

Yesson, C., L. E. Bush, A. J. Davies, C. A. Maggs, J. Brodie. Large brown seaweeds of the British Isles: Evidence of changes in abundance over four decades. Estuar Coast Shelf Sci 155:167-175 (2015c).

Young, M., D. Ierodiaconou, T. Womersley. Forests of the sea: Predictive habitat modelling to assess the abundance of canopy forming kelp forests on temperate reefs. Remote Sens Environ 170:178-187 (2015).

Zavalas, R., D. Ierodiaconou, D. Ryan, A. Rattray, J. Monk. Habitat Classification of Temperate Marine Macroalgal Communities Using Bathymetric LiDAR. Remote Sens 6:2154-2175 (2014).

Zhi, H., J. Siwabessy, S. L. Nichol, B. P. Brooke. Predictive mapping of seabed substrata using high-resolution multibeam sonar data: A case study from a shelf with complex geomorphology. Mar Geol 357: 37-52 (2014).

Tables & Figures

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). Owed 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.

Technique	Description	Advantages	Disadvantages	Macroalgae	Macrophytes
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) Andréfouët et al. (2004b) Dekker et al. (2005) Anderson et al. (2007) Vahtmäe et al. (2007) Cavanaugh et al. (2010) Casal et al. (2011) Tulldhal et al. (2013) Bell et al. (2015) Brodie et al. (2018)	Ferguson et al. (1997) 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) Andréfouët 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) Brodie et al. (2018)	Ferguson et al. (1993) 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) Ŝaŝkov et al. (2015)	Norris et al. (1997) McDonald et al. (2006)

LiDAR	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).	• Large geographic expanses can be sampled quickly • A multitude of sensors can be deployed simultaneously •Information gathered is quantitative	• LiDAR can be restricted in temperate regions due to turbidity • Tides can also effect the consistency and accuracy of classification	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)
Sonar	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).	• Vast expanses of the ocean have already been mapped by governmental and non-governmental organisations and large quantities of data is available open source • Multibeam sonar can cover large geographical areas • Information gathered is quantitative • Sound can travel much further underwater than light mitigating some issues raised by turbidity	• Processing can be time consuming and labour intensive • Multibeam sonar is ineffective in shallow waters (<2m) • Sonar data requires large storage capabilities	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)

Table 4. A selection of citizen science projects, network based initiatives and online repositories of macroalgae data.

Online repositories		
AlgaeBase	AlgaeBase is a species inventory database with country-level distribution data which includes terrestrial, marine and freshwater organisms.	www.algaebase.org
Ocean Biogeographic Information System (OBIS)	Repository gateway to the world's ocean biodiversity and biogeographic data (i.e. museum catalogues and survey records).	http://iobis.org/
Temperate Reef Base	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).	http://temperatereefbase.imas.utas.edu.au/static/landing.html
Citizen science projects		
Nature Watch	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.	http://naturewatch.org.nz/
The Big Seaweed Search	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.	http://www.nhm.ac.uk/take-part/citizen-science/big-seaweed-search.html
Capturing Our Coast	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.	www.capturingourcoast.co.uk/
Atlas of Life	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.	https://www.atlasoflife.org.au/
Floating Forests	Floating Forests is a citizen science initiative to study global distributions of *Macrocystis pyrifera* over a long-term period between 1984 to the present, where the public identify and label satellite images containing kelp.	https://www.zooniverse.org/projects/zooniverse/floating-forests
MarClim Project	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.	www.mba.ac.uk/marclim/

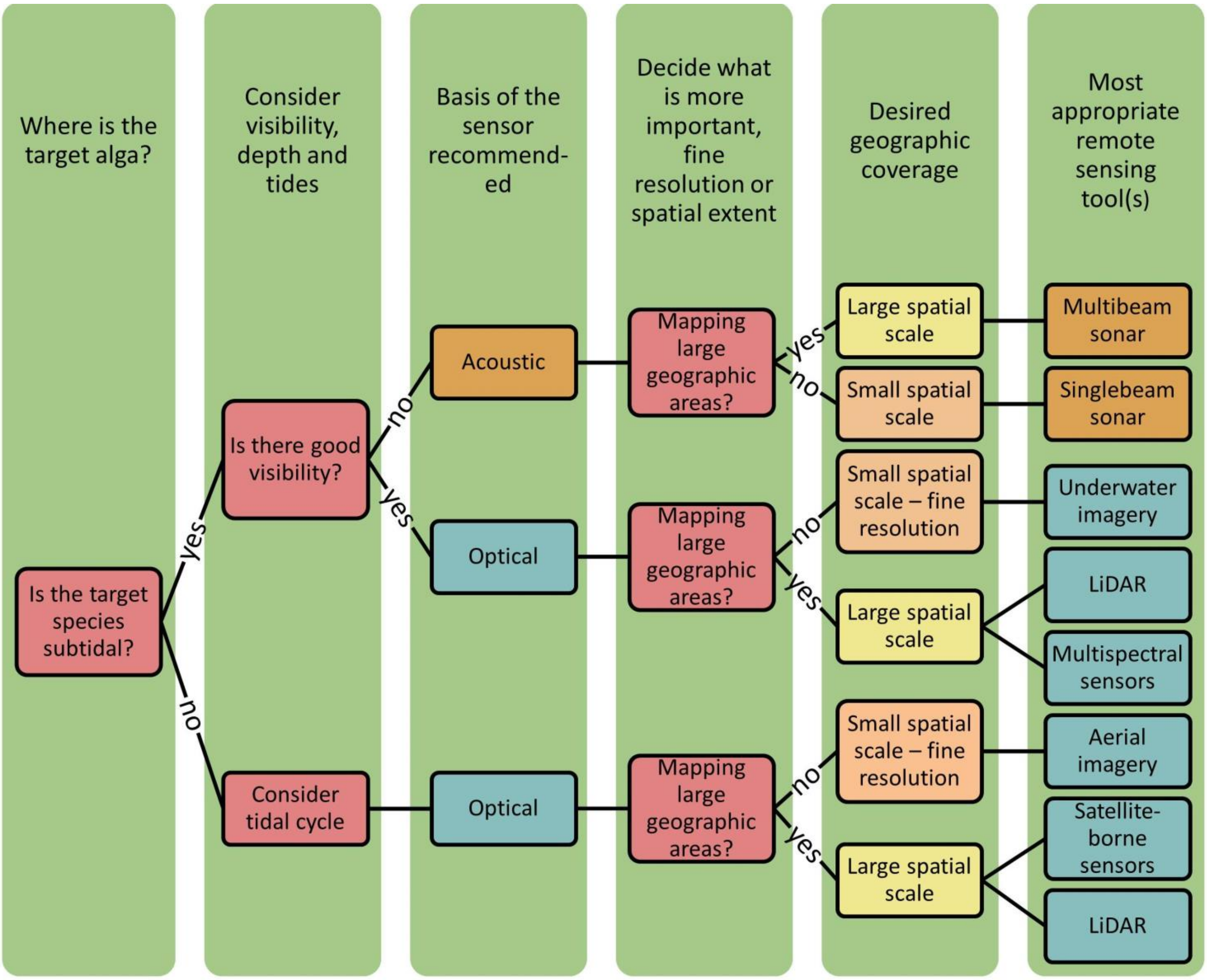

Fig. 1. 'Remote sensing of macroalgae decision tree' provided to aid the selection of appropriate remote sensing tools for mapping submerged and intertidal macroalgae. The detection of submerged algae will likely be best achieved using a combination of acoustic and optical techniques as acoustic sensors are ineffective in water <2 m.