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SAMS
Research Services Ltd

WILD SEAWEED HARVESTING AS A DIVERSIFICATION OPPORTUNITY FOR FISHERMEN

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HIE

Highlands & Islands Enterprise

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Andrew Parker and Emily Thompson from Imani Development undertook economic feasibility analysis of seaweed harvesting, including conducting interviews with various stakeholders and business operators.

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EXECUTIVE SUMMARY

The seaweed industry in Scotland is still in its infancy, but has the potential to thrive and develop to support a range of business that have identified uses for seaweed products. Wild seaweed harvesting can potentially present a unique opportunity for fishermen to diversity their work activities, relieving pressure from fish stocks and providing alternative seasonal income. Although small scale wild harvesting of seaweed occurs around the Scottish coast, the economics and feasibility of large scale wild seaweed harvesting has yet to be examined, with knowledge gaps for sustainability of harvests, environmental impacts and the costs of Marine Licensing.

Scottish waters are considered to have large stocks of *Laminaria,* and it is believed that they may be harvested with tolerable impacts to the natural environment. *Laminaria hyperborea* is not presently cultivated in Scotland, and although experiments are being undertaken in this area, cultivation cannot at present be regarded as an alternative replacement to wild harvesting with respect to providing stocks of kelp to support large scale industry.

Highlands and Islands Enterprise (HIE) contracted SRSL to investigate the potential of wild seaweed harvesting as a diversification opportunity for fishermen. The aim of the project is to deliver a report that covers three areas:

(i) Guidance on the mapping and location of seaweed for harvesting

(ii) Guidance on the harvesting of seaweed

(iii) Marine Licence scoping and economic feasibility of seaweed harvesting

This report is concerned with the potential for medium to large-scale harvesting of kelps in Scotland using mechanical harvesting techniques.

Mapping Kelp Location & Quantities in Scotland

Habitat suitability models were developed for the two major kelp species in Scotland, *Laminaria hyperborea* and *Saccharina latissima*, as well as for two less abundant species *Saccorhiza polyschides* and *Laminaria digitata*. Around the Scottish coast, these models predicted a total biomass of 20 Mt for *L. hyperborea,* 2.5 Mt for *Saccharina latissima,* 188000t (0.19Mt) for *Saccorhiza polyschides* and 161000t (0.16Mt) for *Laminaria digitata*. A total of 6.5 Mt of *L. hyperborea* was predicted for harvestable areas, where biomass per unit area may exceed 5 kg/m^2. Over 75% of predicted biomass of *L. hyperborea* was in three Marine Scotland Atlas regions: West of the Outer Hebrides, the Minch and Inner Hebrides, and the north coast and Orkney.

Model predictions of kelp biomass compared with actual quantities of kelp at surveyed localities show that while the general patterns of abundance are captured, the model over predicts when no suitable bed type is present. This does not mean the model is wrong, but that the underlying seabed data is insufficiently spatially resolved. Suitable baseline surveys of the resource quantities and quality in proposed harvest locations would be required to improve resolution.

From quantities predicted by models it is recommended that any potential harvesting industry for *Laminaria hyperborea* should prioritise areas in (1) the Minch and Inner Hebrides with 35% of the biomass in areas >5 kg/m^2, (2) the west coast of the Outer Hebrides (21%), (3) the North Coast and Orkney (20%), and (4) the combined east and west coasts of Shetland (10%). The predictive kelp habitat layer provides one element of locational guidance for harvesters. However, this is based solely on where kelp may be found. Other environmental factors may make these areas unfavourable to harvest.

A full constraints analysis should be completed for any potential harvesting area to ensure that no protected conservation features are compromised by the planned activity, and that the harvesting does not unduly interfere with existing use of the environment for other purposes.

Such analysis is a normal part of conducting an Environmental Impact Assessment (EIA) and it is recommended that this approach be broadly followed even if a full EIA is not required by the appropriate licencing authority for a kelp harvesting proposal.

Sustainable Harvesting of Kelp Habitats

Kelp habitats support high biodiversity, contribute to marine foodwebs through the production of detritus and provide nursery habitats for invertebrates and fish, including commercially important species. Whilst kelp are vulnerable to a variety of natural factors including grazing by urchins, disease, parasites and storm damage, mature kelp beds are generally thought to be resilient and can persist over many years.

Lessons regarding the impacts of harvesting of kelp are drawn mainly from studies in Norway and France. Harvesting temporarily removes the kelp habitat and results in measurable reductions in associated biota. The kelp itself recolonises and regrows within a few years, but harvesting leads to a more restricted size and age range in the recovering stands compared with unharvested areas. Re-colonisation of the harvested areas is possible, providing there are sufficient source populations nearby. However, full recovery may not be seen within the inter-harvest periods typically applied in Norway. Impacts of harvesting kelp on commercial fish populations are currently difficult to evaluate.

Designing a sustainable harvesting regime is complex and needs to take account of many factors such as the spatial and temporal variability in the resource, the present and future quantities required by processors, the accessibility of sites taking into account typical weather patterns etc. Possible conflicts with other stakeholders including fisheries, tourism, fish farms, and marine renewables also need to be considered. Most present commercial fishing activities are unlikely to be directly affected as mobile gears are not normally deployed in kelp beds, but potting could be affected in some locations targeted for kelp harvesting.

Harvesting plans will also need to have contingencies built in for years where kelp productivity falls due to natural factors. To maintain harvest quantities in such years it would be necessary to harvest a larger area and this must be planned for. The plans also need to be robust to future demand increases and not be susceptible to creeping increases in the area harvested over time.

Due to the multiple factors which need to be taken into account, a 'one-size-fits all' sustainable harvesting strategy cannot be recommended. Site plans would need to be developed and evaluated for specific areas once a developer had chosen a potentially suitable location. However, there are some principles that a harvesting strategy should follow.

It is recommended that kelp harvesting in Scotland follows the practice in Norway, including:

1) Sector-based management in which sectors are open for one year followed by four years' fallow until the next harvesting period.

2) Harvesting in strips one nautical mile wide such that no strip borders one that has been previously harvested. If sufficient kelp habitat is available, each harvested strip should be bounded by permanently fallow (unharvested) strips to ensure proximity to intact forests.

Given a five-year cycle and 15-20% extraction efficiency, in order to sustainably harvest kelp the boundary of the management area should be approximately 33x larger than the area estimated to contain the targeted total yield of kelp (assuming a constant biomass density).

Lease areas should be granted on the condition of a scientifically validated programme of continued assessment of the status of areas to be harvested and those recovering from earlier kelp extraction. Estimation of the occurrence, abundance and biomass of kelp plants should be made using a combination of acoustic estimation of above-bed kelp, kelp bed imaging, and plant size and age from bed samples.

It should be noted that the five-year harvesting cycle may not allow for full recovery of associated biota found on kelp beds. Monitoring of the associated biota will be required to demonstrate recovery of associated communities to a level agreed with the licencing authority.

In terms of surveys to establish baseline environmental conditions, and ongoing monitoring surveys after harvesting has commenced, the following is recommended:

- A pre-harvest assessment should be undertaken across the entire proposed area, comprised of: (i) potential kelp habitats indicated by models; (ii) actual kelp habitats and biomass densities using acoustic methods and towed cameras, supplemented by grab samples.
- Annually, smaller representative areas (n=3) of unharvested/recovered beds and 1 to 4 years' post-harvest beds should be assessed to track rates of recovery of kelp in the area, minimally by acoustic, video and grab methods
- Every five years, kelp habitats and biomass densities should be re-evaluated across the entire area using acoustic methods and towed cameras, supplemented by grab samples. Recovery of kelp-associated ecological communities including epiphytes and fishes should be assessed in selected harvested areas and compared to nearby unharvested kelp habitats, using video and diving methods.
- Independent evaluation of the monitoring data should happen annually, with more in-depth review every five years.

The issue of potential impacts of kelp harvesting on commercial fish stocks is likely to be of concern to stakeholders. Currently, scientific evidence does not clearly demonstrate either certain negative impacts from kelp harvesting on fish stocks, or no measureable impact from harvesting activities on stocks. It is likely additional research is required to ascertain exactly what the consequences of harvesting on fish stocks would be, which may be beyond the capacity of the licence holder.

The normal approach in the UK would be that the developer would bear the cost for conducting baseline surveys and producing appropriate impact assessments, operational and monitoring plans following the normal planning and marine licencing process. Given that the construction of a suitable processing plant would also be required for a viable operation, the normal terrestrial planning process would also need to be followed.

It is recommended that lease areas be assigned to single operators, and that exclusive use be assigned on the basis of demonstrated and continued effort to assess and report the status of the resource and associated biota in the lease area. It should also be a condition that kelp is actually harvested from that area during the licence period to prevent 'land-hoarding'.

The planning and management of harvested areas should be based on an 'adaptive management' approach, whereby data gathered from baseline and monitoring surveys are used to guide developers to the most appropriate way to manage the kelp resource they are harvesting. Such an approach requires the acquisition of robust high quality monitoring data, so that informed decision can be made on the recovery and state of kelp stocks. Harvested quantities should reflect observed recovery rates.

Economic Feasibility

Although it is possible to outline the various steps that a developer will likely need to go through in order to submit an application to obtain a licence to harvest seaweed, it not possible to place an accurate figure as to the cost of undertaking all these activities. Costs will vary on a site by site basis, and will likely be higher the larger the volume of seaweed proposed to be harvested. Whilst the cost of some activities such as obtaining baseline data to characterise a site can be estimated, activities such as undertaking pre-application consultation with local stakeholders are likely to be extremely variable in their significance and magnitude according to the specific location and planned harvesting regime. It is only by starting the process that a developer will get an idea of how much effort and cost will be required submit a licence application for a given area.

Comparisons between the current Scottish fishing fleet to those vessels used in France and Norway for kelp harvesting showed that the majority of the Scottish vessels do not have the requisite characteristics to allow for conversion into a workboat for kelp harvesting. Most Scottish vessels are <10 m, and thus unlikely to be able to transport more than 6 t d^{-1} of seaweed; a 12-15 t d^{-1} load is needed to break even the cost of harvesting. Vessels > 10 m would have higher loading capacity, but most of these operating in Scotland have a closed hold or covered working decks that would make loading and unloading of kelp problematic.

If harvesting is to be carried using local fishing vessels economic analysis suggests that the activity will only be viable for small vessels (<10 m) if kelp is within 15 km of the landing port and a high price is obtained (£40 t^{-1}). For demersal trawlers or medium-sized potters (10-12 m) there is a potentially viable kelp-harvesting envelope out to 25 km, but again only if the price is at £40 t^{-1}. For scallopers (all sizes) and larger potters (>12 m) kelp harvesting does not appear to be an attractive option for diversification because of the relatively high-value of their normal catches.

In case of conversion of local fishing vessels to kelp harvesting, it is recommended to choose those ports that are within 5-15 km from the most productive areas so that more than one harvesting operation can be undertaken in a day. This is necessary because of the limited vessel capacity of the local fishing vessels compared to bespoke vessels used in France and Norway

Although the dedicated Norwegian kelp harvesting vessels have higher capital and operating costs they may be more efficient overall compared to using converted fishing vessels.

Considering the high cost of transporting kelp it is recommended that the processing plant is built close to the most productive harvesting plot, but this will require a further full economic feasibility analysis. The main ports that have sufficient kelp resources within 20 km are in Shetland (Cullvoe, Lerwick and Scalloway), Orkney (Kirkwall) and to a lesser extent the Outer Hebrides (Stornoway).

Dynamic simulations based on discounted cash flow (DCF) confirm that both the French and the Norwegian concepts provide attractive returns at price of kelp higher than £40 t^{-1}. Whatever concept is chosen, based on research market carried out by AB-SIG (2013) to harvest an amount of kelp in the range 20,000 to 30,000 tonnes annually to avoid price distortion (i.e. a drop in the price due to excess of supply).

The amount of harvest suggested by AB-SIG (2013) is compatible with the quantity simulated in the DCF (18,000 t for the French concept and 27,000 t for the Norwegian one). However, it is recommended for the harvesters to negotiate with the industry a price higher than £40 t^{-1}, a threshold under which harvesting by the internal Scottish fishing fleet or by the French model provides negative returns. For kelp price slightly below this threshold (£ 38 t^{-1}) the Norwegian model must be preferred.

International pricing benchmarks are important, but according to the results of the DCF analysis, it is suggested that the following differentiators are considered: 1) proximity to source (freshness), 2) quality and 3) provenance; all of which are also important for processors. A (geographically) closely integrated supply chain would therefore be more likely to deliver high economic benefits – the full value chain benefits, and ability to bear monitoring costs, is the relevant determinant. Scottish harvesting has a differentiated product to international comparators (within limits), and thus can potentially demand a higher price per ton.

The annual value of a licence as one-year lease on the right to harvest has been examined. It is based on the fishing quota model, therefore licence value must be equal to the price of the harvest minus the marginal cost of harvesting. This model works mainly if there are several operators (harvesters) having different production costs, a total allowable catch is set and harvesting quotas can be traded. In this way the quotas of harvesting are distributed by market forces to keep maximum efficiency (operators with lower cost will harvest more). For a single operator a flat cost can be imposed and calculated from the foreseeable net benefits as shown by the DCF.

The annual licence value depends on the harvesting concept used, but for the majority of concepts is in the range £1 - £5 t^{-1}. However, for the more profitable Norwegian trawler the licence cost rises up to £12-£13 t^{-1}. At the average kelp price of £40 t^{-1}, the suggested licence cost should be 3-12% of the total gross income. These values do not consider the cost of monitoring. Therefore, value of licence could be lower than values above suggested, and not to be excluded negative if monitoring / management costs may make sustainable harvesting commercially unfeasible (see implication within supply chain).

The full economic value, instead of the value of seaweed at primary harvesting, can determine the commercial feasibility of operations. High value industries, including pharmaceuticals and food-grade manufacturing and processing, require high quality fresh seaweed that meets sustainability standards. This should justify, and make feasible, monitoring and management requirements that may seem unfeasible when compared to primary harvesting costs, but are as a percentage relatively low in comparison to the value of finished products. Due to promising volumes and quality considerations for *Laminaria* in Scottish waters, the primary seaweed cost per tonne may be higher than less suitable international substitutes. Since the licence-holder is likely to be the buyer/processor, the internalisation of this cost within operations should be viable. Similarly, control and management of the licence process will be aligned with those for whom there is most commercial interest. If, for example, the primary processing cost is £2m per annum and the cost of managing and monitoring impact was an additional £1m per annum, this might appear unfeasible by adding 50% in primary harvesting cost. However, if the licence-holder were operating a £100m biotech processing business, the cost would be an additional 1%, which would be, at worst, a lesser determinant of viability than many other considerations.

By the same measure, for lower value uses (for example, fertiliser or biofuel uses), the monitoring/management costs may make sustainable harvesting commercially unfeasible. However, it would be for the individual companies to determine viability based on monitoring and licensing requirements and their cost structures.

Licensing plans should be well aligned with the operational and management controls required: licensing, management and monitoring costs should be as low cost as possible while meeting robust regulatory standards. On a primary harvesting price basis, these may seem unfeasible, but looking at the full value potential for a licence-holder is more relevant: i.e. seaweed harvesting should not be dismissed on the basis that adequate monitoring and management costs seem high at primary level, because the potential benefits elsewhere may justify robust monitoring requirements for many applicants.

Licensing costs (including ongoing monitoring and management requirements) can be sustainable for the harvesting industries, depending on the full economic value of their business.

It is recommended that efforts are made to devise the lowest cost management and licensing regime possible to meet requirements, and allow applicants to judge if their supply chain model can support those costs – because it may be viable beyond primary harvesting cost considerations and offer considerable economic benefits.

The commercial viability of a harvesting enterprise will still depend on a common understanding of requirements between regulators and industry – this means clear, predictable expectations on what is acceptable and what is not. Regulators should give a clear framework of expectations and costs of management and monitoring. Within this document an outline of the steps that a developer will have to go through to obtain a licence is provided as a starting point to help guide harvesters.

Similarly, a broader challenge is the social acceptability of harvesting seaweed – use of seaweed in Scotland is a traditional activity, but modern harvesting is an unfamiliar process to coastal communities. Attention should be paid early on in the process to ensuring the full benefits of any activity are communicated to stakeholders, possibly with direct benefits agreed.

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1 INTRODUCTION

1.1 History of Kelp Harvesting in Scotland

Small-scale harvesting of seaweeds has taken place in Scotland for hundreds of years for use as a fertiliser on the poor coastal soils (Angus, 2017). However, in the 18th century British industry increasingly depended on soda ash derived from burning kelp (*Laminaria* spp.) or wrack (*Fucus* spp.). Kelp was collected during the summer months in western Scotland and annual harvests grew to as much as 25,000 tons, providing seasonal employment for perhaps as many as 10,000 families (Hothersall, 2012; Angus, 2017). Kelp as a source of alkali was eventually replaced by the chemical Leblanc process and by the 1830s its use for alkali production had largely disappeared (Keifer, 2002).

Kelp has also been harvested as a source of iodine but its main industrial use has been as a source of phycocolloids. The three main phycocolloids are the alginates, agars, and carrageenans. Phycocolloids are polymers of modified sugar molecules, such as galactose in agars and carrageenans, or organic acids, such as mannuronic and glucuronic acid in alginates. Alginates are extracted mainly from brown seaweeds whilst agars and carrageenans are extracted from red seaweeds. Alginates were first extracted from seaweed in 1883 by a Scottish chemist, E.C.C. Stanford but industrial production did not begin in Scotland until the 1930s by the Cefoil company based in Kintyre. Extraction expanded during World War II with additional factories opened at Kames, Barcaldine and Girvan. These factories produced, among other products, chromium alginate which was used in camouflage netting.

After the war the alginate industry continued to grow and new sources of seaweed were sourced from Ireland, Norway and Iceland, but also as far afield as Chile and Tasmania. A series of extensive surveys for seaweed was also conducted around Scotland by the Scottish Seaweed Research Association (later named the Institute for Seaweed Research), recognising the national importance of this resource (Walker, 1947; Chapman, 1948; Walker, 1954).

In the late 1970s increased competition from China led to the Scottish alginate industries being taken over by Kelco/Alginate Industries Ltd. The Barcaldine plant was closed in 1996 and Scottish alginate production concentrated in Girvan. The alginate arm of Kelco was then sold to International Speciality Products (ISP) in 1999. In 2009 ISP sold the alginate business to FMC which became part of Pronova, a Norwegian producer. Alginate production ceased at Girvan, although the plant was kept open for blending and product distribution.

Dried and ground seaweeds are now used quite extensively in agriculture (Makkar et al. 2016) and human nutrition as food supplements but the main industrial demand is for extracted alginates. These compounds have a wide range of applications in food production, pharmaceuticals, textiles, paper and biotechnology where they are used as thickening, gelling, absorbing, varnishing, agglutinating and waterproofing agents (Mesnildrey *et al*., 2012).

1.2 Current Activity

Continuing increases in demand for alginates have led to increasing interest from industry in the Scottish kelp resource and in whether its harvesting could be revived and expanded. There is also interest in whether this could provide diversification opportunities for the inshore fishing industry.

The only current medium to large-scale seaweed harvesting operation in Scotland is for rockweed (*Ascophyllum nodosum*) in the Outer Hebrides, which is harvested by the Hebridean Seaweed Company. The raw material is collected either by hand or by using small specialized cutting and collecting boats. The products are used in animal feeds, soil enhancement, alginate, cosmetics and nutraceutical industries. The permitted harvest rates are guided by a HIE/Scottish Enterprise report (Burrows *et al*., 2010), which estimated the stock size (170,000 t), the amount within economical transport distance (3 km) of landing sites (60,000 t), the maximum safe removal rate (25%) and thereby the maximum recommended annual landing (15,000 t). Stocks in the Outer Hebrides were estimated using a combination of habitat modelling and field surveys: an approach adopted in this report, albeit with a smaller quantity of survey data for the less easily accessible kelp resources.

1.3 Strategic Environmental Assessment

Potential plans for the harvesting of wild seaweed in Scotland beyond the small-artisanal scale were considered to have sufficient potential environmental impacts that they would fall under the EU's Strategic Environmental Impact (SEA) Directive (European Parliament and the Council, 2001), as transposed into the Environmental Assessment (Scotland) Act of 2005. An SEA on seaweed cultivation had been previously undertaken, which included a high-level assessment of the potential effects of harvesting wild seaweed, but this analysis was not considered detailed enough to inform decision making. The Scottish Government therefore produced an SEA report in 2016 titled '*Wild Seaweed Harvesting Environmental Report'* (Scottish Government, 2016), which focussed on the sustainability and potential environmental and cumulative impacts of large scale mechanical extraction of wild seaweed, in particular kelp forests.

The SEA assessed impacts on biodiversity, climate and cultural heritage but did not examine the economics of large-scale seaweed harvesting, or potential conflicts of large-scale harvesting with other marine sectors. In terms of ecological impacts, the SEA concluded that significant adverse effects can occur as a result of large scale (i.e. industrial) mechanised harvesting of seaweeds (namely kelps and wracks). The main issues identified were:

- Loss of habitat and/or shelter for a range of plants and animals, alongside loss of direct and indirect food sources. This has consequences for detrital grazers and suspension feeders, as well as higher trophic levels including mammals, birds and fish;
- Loss of nursery grounds for juvenile invertebrates and fish, with consequences for higher trophic levels and commercial fish stocks;
- Loss of the physical modification effects of seaweed, e.g. wave damping, which may result in increases in coastal erosion and/or flooding events;
- Loss of carbon stores and sinks provided by some seaweed species; and

- Loss or damage to cultural heritage assets and reduction in resource available to crofters.

These potential effects are site-specific and will vary according to the location, type and extent of activity. Ensuring sustainable harvesting requires understanding characteristics of the harvesting, principally the target species and the extent and scale of harvesting (i.e. frequency of harvesting, the proportion of a seaweed community harvested the amount (Scottish Government, 2016).

1.4 Purpose of this Report

Understanding the size of Scotland's kelp stocks, the likely size of any potential harvest, and the potential impacts on the shallow water ecosystem are vital first steps in establishing the potential for large-scale seaweed harvesting in a sustainable and environmentally acceptable manner.

To inform on-going understanding of the potential development of the seaweed harvesting sector as a diversification opportunity for fishermen, this report address the following objectives as set out by HIE:

1. To map the distribution of *Laminaria* around the Scottish coast line and identify potential harvesting locations.

2. To produce a guidance document that addresses the impact of seaweed harvesting on the environment and other industries i.e. fishing.

3. To provide guidance on the requirements of the MS wild harvesting licensing process and identify whether seaweed harvesting is an economically feasible diversification opportunity for fishermen.

For Objective 1, estimates of the location and quantity of kelp species across Scotland were made using predictive models (Burrows *et al*., 2014c), and compared with earlier surveys conducted in the 1940s and 1950s. Five species of kelp were identified as present in Scotland: (1) tangle, *Laminaria hyperborea*, (2) sugar kelp, *Saccharina latissima,* (3) furbelow, *Saccorhiza polyschides*, (4) oarweed, *Laminaria digitata* and (5) dabberlocks, *Alaria esculenta*, but only *Laminaria hyperborea* (and to some extent *L. digitata*) was considered likely be the main targets of medium- to large-scale harvesting for industrial uses. Although the blades of *Saccharina* species contain a wide range of valuable chemicals, this species rarely lives in areas where it can be harvested on a large scale in Scotland and it is more likely to be a target for cultivation (Angus, 2017). Each of these species has distinct ecological characteristics that influence their distribution and sustainability of any potential harvesting.

The second part of the report develops guidance related to the potential impact of seaweed harvesting on the environment and other industries. As no kelp harvesting industry is currently established within Scotland, this is based on a review of evidence, best practice and expertise from other countries where kelp harvesting is currently occurring, including Norway and France. The techniques and types of vessels used in seaweed harvesting elsewhere have also been reviewed, and compared to the composition of the current Scottish fishing fleet to see if parallels can be drawn.

Finally, the third part of the report looks at processes and information requirements of the licensing of harvesting activities and the economic feasibility of wild harvesting. A step-by-step process to guide an applicant through the licensing process in Scotland is included. The economic feasibility of kelp harvesting as a diversification for Scottish fishermen is assessed based to types of vessel and modelling discounted cash flow. Estimates of the cost for obtaining a seaweed harvesting licence are examined, along with an assessment of the value chain for the industry.

2 SEAWEED MAPPING AND LOCATION GUIDANCE

This section of the project aimed to predict suitable areas for kelp habitats and to estimate quantities of kelp, including *Laminaria* species, around the coast of Scotland and the Islands, thereby indicating potential areas of substantial kelp availability around the Scottish coast.

The specific requirements of the different kelp species allow their geographical distribution to be modelled based on data detailing factors such as bottom type, depth, illumination and wave exposure (Bekkby *et al*., 2009, Méléder *et al*., 2010). Given the challenges of gathering data on actual distribution, a model was used to predict potential areas kelp habitat and therefore of potential interest for large scale harvesting activity, based on previous models (Bekkby *et al*., 2009; Méléder *et al*., 2010; Burrows, 2012; Burrows *et al*., 2014a; 2014c; 2016). Given the challenges of gathering data on actual distribution, a model was used to predict potential areas kelp habitat and therefore of potential interest for large scale harvesting activity, based on previous models.

To improve the accuracy of the predictions and to further understanding of the potential location and scale of seaweed harvesting in Scotland, three areas were selected from among those areas identified from the models as having sufficient biomass of *Laminaria* to be possible seaweed harvesting locations. These were further surveyed using acoustic techniques, underwater cameras and diver surveys of kelp populations to determine likely yields. Abundance estimates were converted to biomass using relationships between biomass and percentage cover from diver surveys and literature (as in, for example, Kain, 1977). The surveys represent the expected form of the methods expected to be used for on-going evaluation of the potential for the industry to expand. More detailed site-specific survey work will be required to inform sustainable management at particular locations. It must be recognised that these surveys cover a very small proportion of the potential harvesting areas across Scotland. The combination of modelling and survey methods aims to bridge the information gaps in seaweed distribution at a range of scales, from high-uncertainty large-scale estimation using models, through medium-uncertainty measurement using acoustic techniques, through low-uncertainty video and diving assessments giving confirmation of species identities and measurements of the size and abundance of the seaweed plants themselves.

The primary target for large-scale harvesting from floating vessels in Scotland are the large brown subtidal kelp and are therefore the focus of this mapping exercise rather than intertidal species such as dulse (*Palmaria palmata*) that are generally collected by hand from the shore. Kelp is found at sub-tidal depths in the photic zone anchored to stones, boulders and rocky substrate. In coastal waters, light penetration sufficient to support kelp growth is limited to around 15 m, although in clear Atlantic water they can grow down to 40 m. Kelp plants extend up to the lowest intertidal area, just above the low water mark and different species prefer different wave exposure conditions (Hawkins & Harkin, 1985).

The different species of kelp have varying characteristics, which influence their suitability as harvesting species. *Laminaria digitata* has a flexible stipe allowing it to cope with occasional exposure and with turbulent water flow and wave action so it is found in exposed situations. *Laminaria hyperborea* is less well adapted to wave impacts having a more rigid stipe, but it can generally outcompete *L. digitata* in the lower light conditions of the mid-sublittoral zone. *Laminaria digitata* is also longer lived than the other species (Table 1). *Laminaria digitata* and *L. hyperborea* form extended monospecific kelp beds and this, along with their alginate content, make them the main target species for kelp harvesting in the north-east Atlantic.

Other species of potential interest include:

- *Saccharina latissima* (sugar kelp), which prefers sheltered waters and has a long narrow, undivided blade that can grow to 5 m.
- *Saccorhiza polyschides,* which has a divided blade and grows to 2-2.5 m. It is opportunistic with a high growth rate but it also has a high light demand. It can therefore develop quickly in denuded areas and may outcompete other kelps (Kain & Jones, 1969; Werner & Kraan, 2004).
- *Alaria esculenta*, which can reach lengths of about 2.5 m. It is found in very exposed sites in the upper sublittoral although it can also be found in deeper water but only in places where *L. hyperborea* is lacking due to very strong wave action.

The characteristics of the various species are summarised in Table 1, which includes details such as the northern and southern limits to the distribution of each kelp species, depth and life span.

Table 1. *Characteristics of the main kelp species found in Scotland and Ireland*

Species	**Commercial interest**	**Distribution (Northern – Southern limits)**	**Depth**	**Exposure**	**Life span (y)**	**Reference**
Laminaria hyperborea	Y	Iceland, Russian coast (Murmansk) - Portugal	Mid-sublittoral	Medium-high	10-15 5-18	Werner & Kraan (2004) Smale *et al*. (2013a)
Laminaria digitata	Y	Spitsbergen - Brittany/France	Upper-mid-sublittoral but tends to be outcompeted by *L. hyperborea* at depths > 3 m	Medium-high	3-5 4-6	Werner & Kraan (2004) Smale *et al*. (2013a) Hawkins & Harkin (1985)
Saccharina latissima	N	Spitsbergen - Portugal	Upper-mid-sublittoral	Medium	2-5 2-4	Werner & Kraan (2004) Smale *et al*. (2013a)
Saccorhiza polyschides	N	South Norway - Morocco	Upper-mid-sublittoral	Medium-high	1-1.5 1	Werner & Kraan (2004) Smale *et al*. (2013a)
Alaria esculenta	N	Spitsbergen - Brittany/France	Upper-mid-sublittoral	High-very high	4-5 4-7	Werner and Kraan (2004) Smale *et al*. (2013b)

2.1 Current Understanding of Kelp Habitat Distribution in Scotland

The locations of kelp beds around Scotland were assessed in the 2016 SEA (Scottish Government, 2016) based on available habitat and observational information. The main areas identified were along the Scottish west coast, to the north-east of Orkney and around Shetland. Kelp is less common on the east coast of mainland Scotland as much of the seabed is sandy. Total coverage was estimated at between 10,004 and 15,042 km^2 depending on which model was used (Burrows *et al*., 2014b). Areas with sufficient resource to make potential harvesting sites were evaluated in the SEA report and these models have been updated in the present report.

Detailed surveying by aerial photography and grab surveys produced a comprehensive view of the distribution of kelp around Scotland in the 1940s and 50s (Walker, 1954), with 10 million tons estimated for economic harvests. Most kelp was found to be in Orkney (1.7 Mt), Shetland (0.6 Mt) and the Outer Hebrides (0.7 Mt). The Marine Nature Conservation Review of the Joint Nature Conservation Committee (Hiscock, 1996) made over 5,000 dives at 3,500 locations in kelp habitats around Scotland and the UK, showing the distributions of the main species and their associated communities changes along gradients of wave exposure and light attenuation (Burrows, 2012). More recently, from a policy perspective, the need to protect kelp habitats has prompted efforts to measure habitat condition (Burrows *et al*., 2014c), and to determine kelp's role in sequestration of carbon, particularly in marine protected areas (Burrows *et al.,* 2014c; 2016). These assessments use models built using associations between kelp abundance and environmental measurements, similar in approach to those made in other countries such as Norway (Bekkby *et al*., 2009) and France (Méléder *et al*., 2010). In this study, we extend this method using better bathymetric data and improved statistical methods. Vessel-based acoustic surveys using single beam sonar supported by drop down camera observations, complemented by diver surveys were planned, with diver survey data used to validate model predictions.

The earlier survey efforts of the Scottish Seaweed Research Association/Institute of Seaweed Research (SSRA/ISR) in the post-war 1940s and 1950s and the later efforts of the Marine Nature Conservation Review (MNCR) in the 1980s and 1990s achieved an intensity and coverage of survey effort that would be unlikely to be commissioned today. The many SSRA/ISR reports, held in the SAMS library as an archive after the winding up of the ISR, are a valuable resource. The quantitative information in these reports and the associated publications are a useful comparison with predictions from habitat suitability models and the results of present-day surveys.

2.2 Creating Predictive Maps from Models

Maps have been created by refining and applying predictive habitat suitability models from previous estimations of kelp biomass around Scotland (Burrows, 2012; Burrows *et al*., 2014a; 2014c; 2016). Data on kelp abundance and their environmental predictors have been collated from known sources. Models and maps have been created for the two main species of kelp in Scottish waters, *Laminaria hyperborea* (tangle) and *Saccharina latissima* (sugar kelp) and for the less abundant species *Saccorhiza polyschides* and *Laminaria digitata*. Because the primary available abundance data are expressed as abundance categories based on the percentage cover observed during dive surveys, models initially predicted the likelihood of kelp exceeding a particular abundance threshold using ordinal logistic regression. These likelihood estimates were first converted to biomass predictions using assumptions about the relationships of the biomass of kelp species to their percentage cover (as in, for example, Kain, 1977). Survey data collected during the project were subsequently used to replace literature estimates of biomass per unit area.

2.2.1 Data available on kelp abundance and presence

The approach adopted for this report was to produce a medium resolution model of the suitability of habitat around the Scottish coast for commercially harvestable kelp species. The primary source of data on kelp abundance and presence was the Marine Nature Conservation Review (MNCR) of the UK Joint Nature Conservation Committee (JNCC), obtained by direct download from the National Biodiversity Network Gateway. Divers using SCUBA surveyed specified depth ranges using MNCR Phase 2 survey methods (Connor & Hiscock, 1996). All kelp species present were recorded on these surveys using categorical abundance scales based on kelp density expressed as numbers of plants per m^2 or percentage cover of the substratum (Table 2). The same surveys recorded the abundance of other species in the area, typically 20-40 species from a checklist of over 100.

Table 2. *MNCR Abundance categories for kelp species*

Category	[**S**] Super-Abundant	[**A**] Abundant	[**C**] Common	[**F**] Frequent	[**O**] Occasional	[**R**] Rare
Density (plants/m^2)	>9 /m^2	1-9 /m^2	1-9 /10m^2	1-9 /100m^2	1-9 /1000m^2	<1 /1000m^2
Percentage cover	>80%	40-79%	20-40%	10-20%	5-9%	1-5% or density

From 1977 to 1998, typically 100 to 300 surveys were done annually, visiting different regions around the UK coast each year and including most of Scotland and the outer islands. Locations were recorded to the nearest 100 m using Ordnance Survey grid coordinates. A total of 5,959 surveys were available in the dataset from 3,254 unique locations, with two or more depth ranges surveyed at each location.

This data provides an unparalleled resource for estimating the habitat requirements of subtidal species around the UK (Burrows, 2012). The kelp models for this report were built on the statistical associations between kelp presence/abundance and mapped data on the main environmental drivers of kelp abundance.

2.2.2 Environmental predictors of kelp abundance

The rationale behind each choice of environmental predictor is summarised here, with sources of data given in Table 3.

1. **Depth.** This is the main determinant of kelp abundance, with kelp only found in depths to which sufficient light penetrates for growth and survival of plants, from a few metres in areas of suspended sediments to 30-40 m in exceptional clear areas. Bathymetry data came from the EMODNET dataset, with an initial resolution of 50 m. Where inshore bathymetry was unavailable in the EMODNET dataset, depth values were replaced with those from the Seazone dataset.

2. **Wave fetch.** Wave climate was represented by a modelled wave-fetch layer (Burrows *et al.,* 2008; Burrows, 2012). Fetch is the distance to the nearest land from a point on or near the coast, and gives a useful proxy for local wave conditions. Large values indicate the greater wave heights and longer wave periods of wave-exposed coasts, with small values of summed fetch found inside sealochs. Wave fetch was predicted using an iterative model that searched for the nearest land in a series of sectors around each focal point along the coastline, repeated for every coastal grid cell (all 200 m grid-squares <5 km from the coast across the UK, Figure 1 right). Wave fetch beyond 5 km from the coastline was estimated from the relationship between wave fetch and average wave height for offshore areas around Scotland (derived from UK Atlas of Marine Renewables data, Figure 1 left).

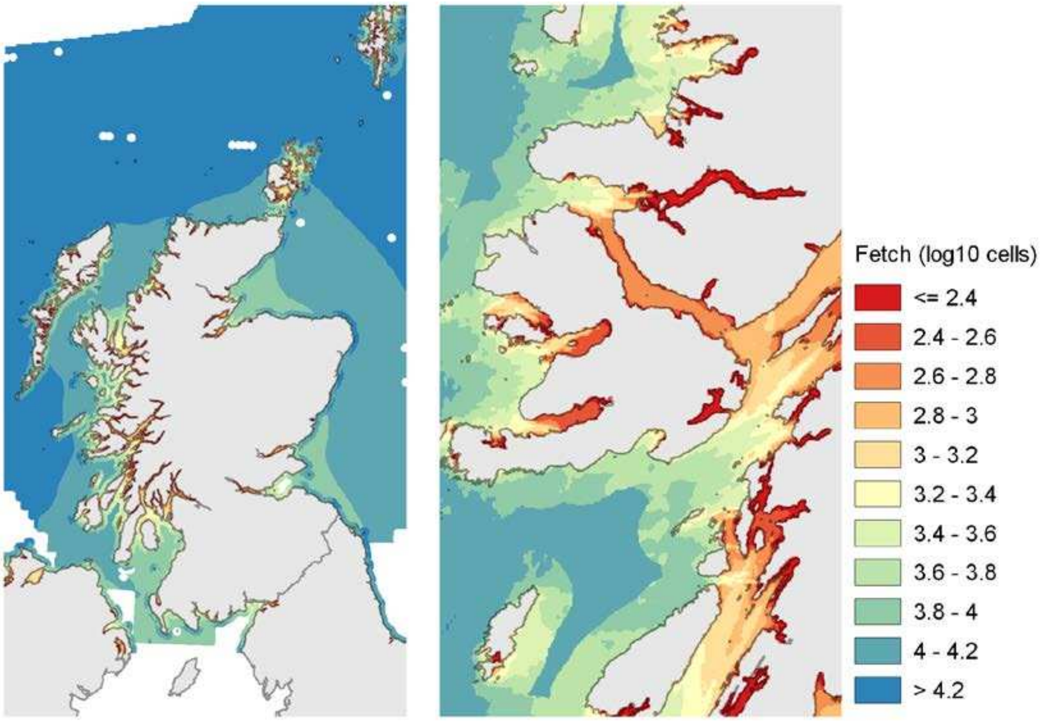

Figure 1. *Wave fetch (left) around Scotland, and (right) in W Scotland showing wave-exposed (blue) and wave-sheltered areas (red), typical of* Laminaria hyperborea *and* Saccharina latissima *habitats respectively.*

3. **Ocean colour**, as estimated chlorophyll *a* concentration. Satellite data on ocean colour, obtained from the NASA Giovanni online data portal (NASA 2009), is a good indicator of the degree of light attenuation in the water column: a key predictor of the depth to which kelp can growth (the photic zone). Data were obtained at 4.5 km resolution (Figure 2) and resampled to the same 200m grid as the wave fetch data.

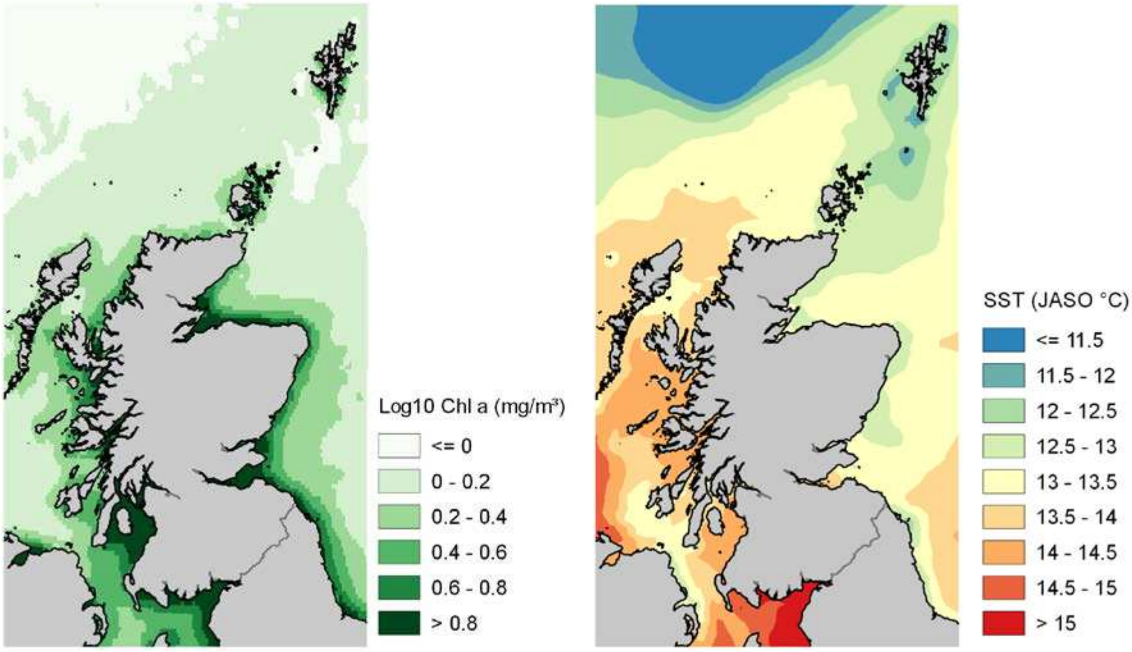

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Figure 2. *(left) Average chlorophyll* a *concentration around Scotland, showing areas of limited light penetration and restricted depth of kelp. (right) Average summer (July, August, September, October) sea surface temperature*

4. **Seabed type.** Kelp needs a hard substrate to attach and grow. Sand, mud and gravel areas are unsuitable for kelp, while mixed sediment areas may have rocks and boulders that permit the growth of kelp. Information on seabed type in shallow areas (0-40 m depth) was not widely available at the scales required for this project, since much of these areas are inaccessible for survey vessels, resulting in the so-called ‘white ribbon’ of data scarcity below the low water mark. In the absence of this information, the substrate type of the nearest intertidal area was used as an indicator of the likely type of nearby subtidal seabed.

5. **Temperature**, data from satellite infrared sensors and from local oceanographic models. Kelp abundance changes with temperature over the geographical range of each species, typically declining towards the southern, warm edge of their ranges. Most kelp species in the UK have their distributions centred in colder waters, with kelp abundance less on southern coasts than those in Orkney and Shetland. Annual average temperatures do not vary by much across Scotland, however, and the range from 9.5 to 11.0 °C has little effect on this geographical scale. Initial trials showed that summer temperatures (average July, August, September, October) best predicted the distribution of kelp species around the UK.

6. **Tidal flow.** Although having similar effects on kelp community structure to those of wave fetch (shifts to wave-exposed species), this additional information was explored as a potential predictor for kelp abundance in high flow areas. Data were obtained from the UK Atlas of Marine Renewables. The data on bottom flow (expressed as tidal power in W/m^2) was a modelled data product derived from a 1.8 km depth stratified model originally produced by the Proudman Oceanographic Laboratory (now NOC Liverpool). The coverage of this model was generally good, but omitted some important tidal narrows between islands in West Scotland. Initial exploration of the utility of tidal flow information showed that the flow was correlated strongly with coastal wave exposure, and that including the term in statistical

models of kelp habitat suitability did not improve the predictive power of the models. Tidal flow information was thus dropped from the model.

2.2.3 Data manipulation and mapping

Gridded spatial data were transformed from the original coordinate system (WGS84 latitude/longitude for depth, ocean colour, sea surface temperature) into Ordnance Survey coordinates (OSGB 1936) to allow equally sized grid cells (200 m x 200 m = 40,000 m^2 or 0.04 km^2) and to align with pre-existing modelled data on wave fetch. Satellite-derived data products (ocean colour, temperature) had a coastal 'mask' applied, such that areas in the original dataset that included any land were removed from the dataset. This presented a problem for predicting effects of these factors at the coast. Neighbourhood averages of each predictor (chlorophyll *a* mg/m^3, temperature) were produced for a range of neighbourhood sizes, from 3x3 (15 km), through 5x5 (25 km) to 11x11 (55 km). Values for the predictors in masked areas were estimated from these neighbourhood averages. Missing values were replaced by 3x3 averages, with any remaining missing values sequentially replaced by 5x5 averages and ultimately 11x11 averages. This process created synthetic datasets for chlorophyll *a* and temperature that represented expected values in coastal areas as the averages of the nearest areas of open sea.

Table 3. *Sources of data for kelp presence, abundance and biomass, and predicting suitability and biomass*

	Source	**Access**	**Period**	**Extent**
Kelp				
Kelp presence/ abundance	Marine Nature Conservation Review (JNCC)	nbn.org.uk	1977-1998	UK-wide
Kelp biomass	Kain (1977)	From figure (Fig. 1)	1972-1976	West Scotland and Irish Sea
Kelp plant size, density and estimated biomass	Smale, Moore (this study)	Diver surveys	2017	Orkney, Kintyre
Environmental Predictors				
Depth	European Marine Observation and Data Network EMODnet	http://www.emodnet.eu		UK- and Europe-wide
Wave fetch	Burrows (2012)	Marine Scotland - National Marine Plan Interactive https://marinescotland.atkinsgeospatial.com/nmpi/		UK- wide
Ocean colour: Chlorophyll *a* mg/m^3	MODIS Aqua Satellite L3m analysis product	NASA Giovanni data portal https://giovanni.gsfc.nasa.gov/giovanni/	2002-2010	UK- and Europe-wide
Substratum type	Defra, CCW Intertidal substrate type	Defra		England, Scotland, Wales
Sea surface temperature	MODIS Aqua NEMO-ERSEM	NASA Giovanni NOC	2002-2010 1989-2014	UK- and Europe-wide
Tidal flow	UK Atlas of Marine Renewables	http://www.renewables-atlas.info/		England, Scotland, Wales

2.2.4 Model construction and implementation

Statistical associations between kelp abundance were quantified using the R statistical package (R Core Team, 2017). Locations from the MNCR dataset were used to extract values for each survey of wave fetch, chlorophyll *a* and average summer temperature from gridded data. Categorical abundance data for kelp species (tangle, *Laminaria hyperborea*, and sugar kelp, *Saccharina latissima*, along with furbellows, *Saccorhiza polyschides*, and oarweed*, Laminaria digitata*) were used as response variables in generalised additive models with a binomial link function using the R gam function; predicting the likelihood of presence of kelp as a function of the combined effects of the environmental predictors. Responses to each predictor were characterised by smoother functions, fitted jointly to depth, wave fetch and chlorophyll concentrations and separately to summer temperatures. The further likelihood of each of the kelp SACFOR abundance categories, above "Rare", was estimated using information from ordinal logistic regression (intercept parameters relative to the baseline (>=R) presence).

Model predictions for kelp likelihood were produced using data for the entire UK to enable comparison with kelp biomass measurements in other areas. Applying the model across this larger spatial domain did not affect predictions for Scotland, since temperature effects on kelp abundance between southern and northern parts of the UK were accounted for by the temperature term in the gam model (Annex A).

Further details on the kelp habitat suitability model are included within Annex A, including all limitations and assumptions behind the implementation of the model. For example, the Annex covers how kelp abundance records were converted into biomass, and how the model was further validated and refined by site surveys using underwater diving and vessel based acoustic and drop-down camera systems.

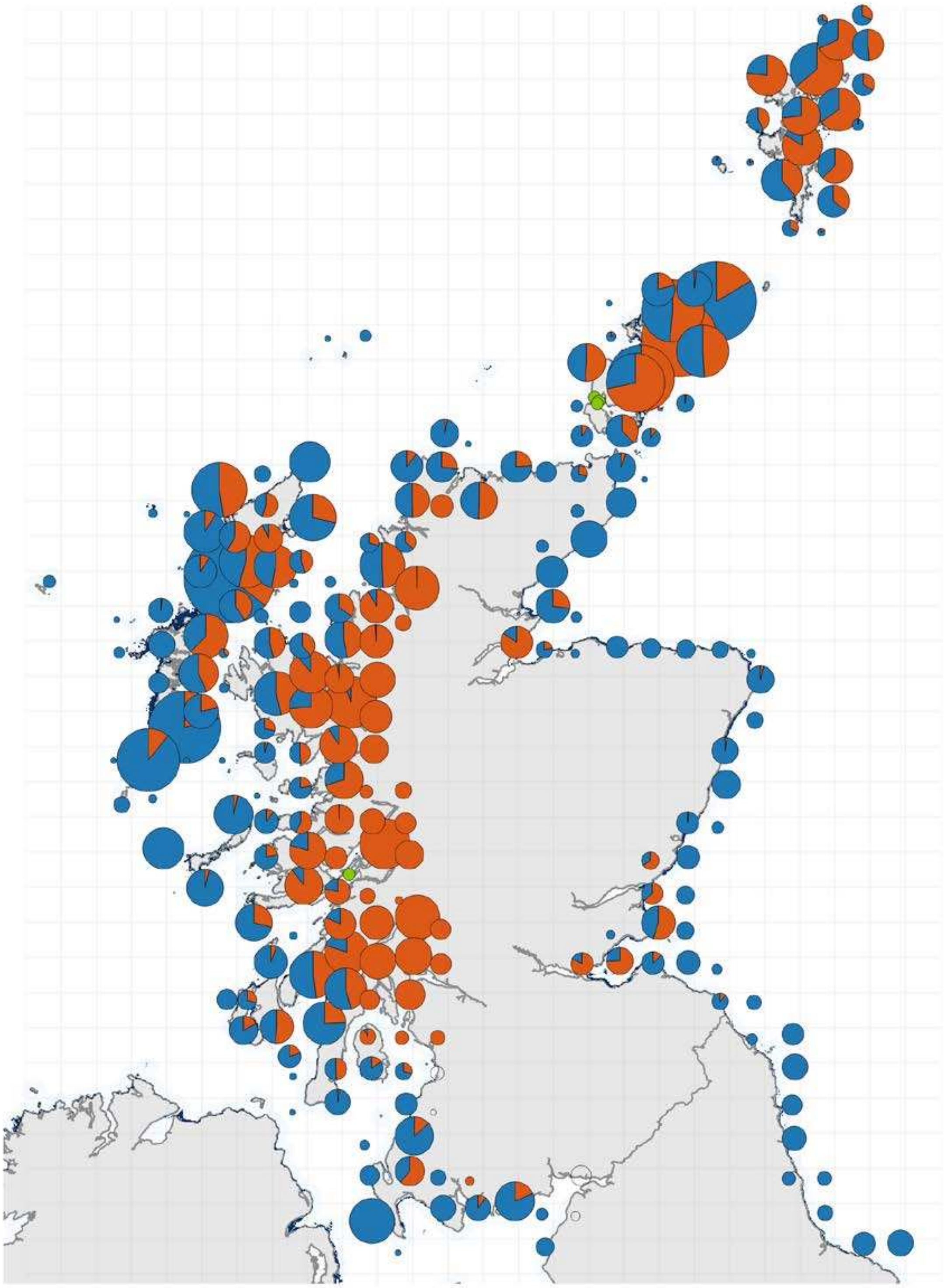


Figure 3. *Predicted distribution of suitable habitat for tangle* Laminaria hyperborea *(blue) and sugar kelp* Saccharina latissima *(orange) around Scotland. Pie charts show the percentage of the total suitable habitat (P (kelp)>50%) for each species in 20 km grid squares. The size of each circle is scaled to the estimated suitable habitat for both species combined.*

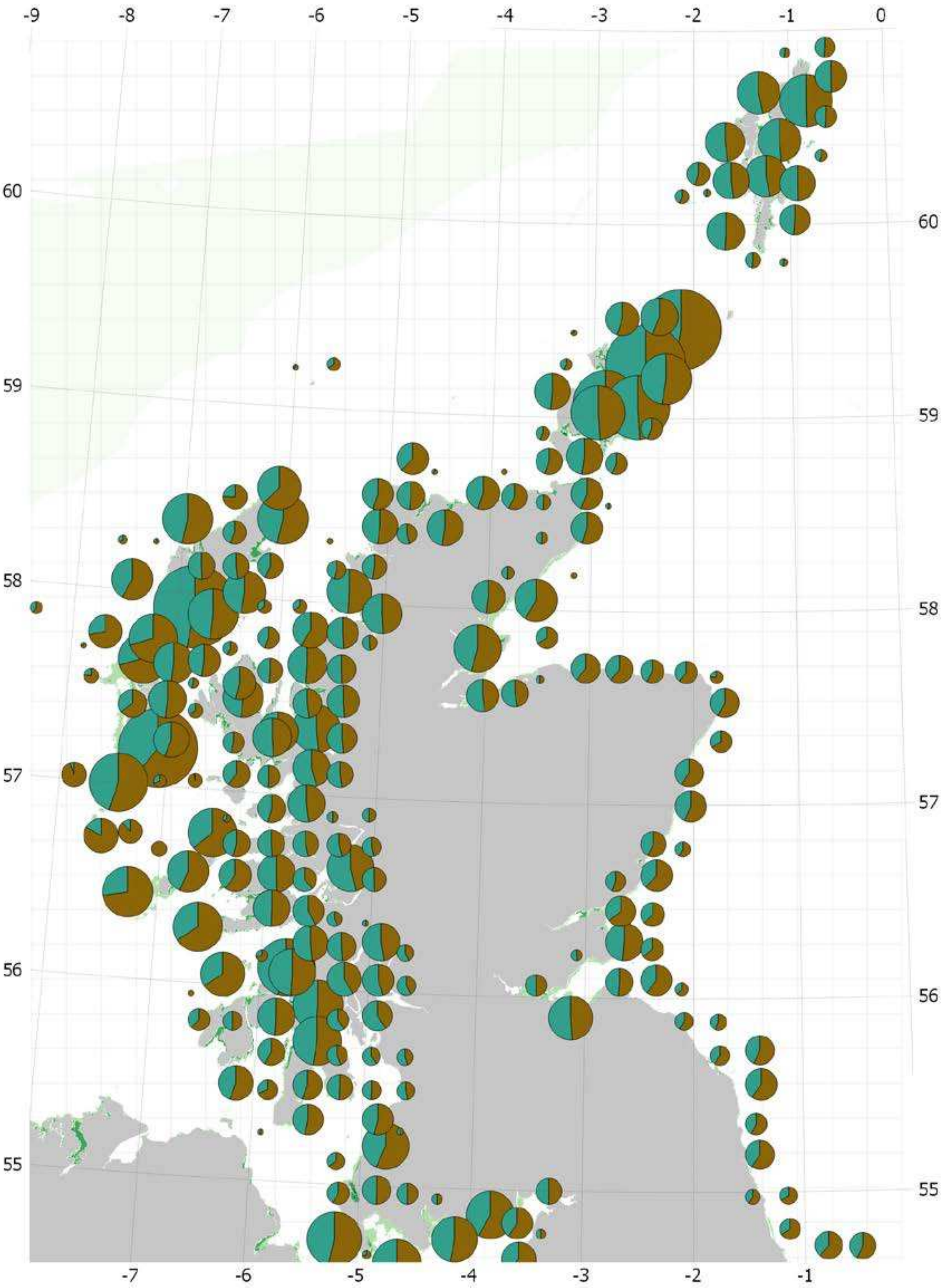


Figure 4. *Predicted distribution of suitable habitat for furbellows,* Saccorhiza polyschides *(blue-green) and oarweed* Laminaria digitata *(brown) around Scotland. Pie charts show the percentage of the total suitable habitat (P (kelp)>10%) for each species in 20 km grid squares. The size of each circle is scaled to the estimated suitable habitat for both species combined.*

2.3 Model Predictions of Suitable Areas for Kelp

Across Scotland, predicted areas of habitat suitable for *Laminaria hyperborea* and *Saccharina latissima* (expressed here as areas where kelp is more than likely to be found in an MNCR-style dive survey, P(kelp being at least Rare)>0.5) were predominantly in the west and north, with much less on the east coast (Figure 3). Wave exposed, clear water areas of the Inner and Outer Hebrides were predicted to have greater areas of suitable habitat for *Laminaria hyperborea*, while *Saccharina latissima* (sugar kelp) was predicted to be the dominant species in the sheltered waters of west coast sealochs, in the lee of coastal islands and in the firths and voes of Orkney.

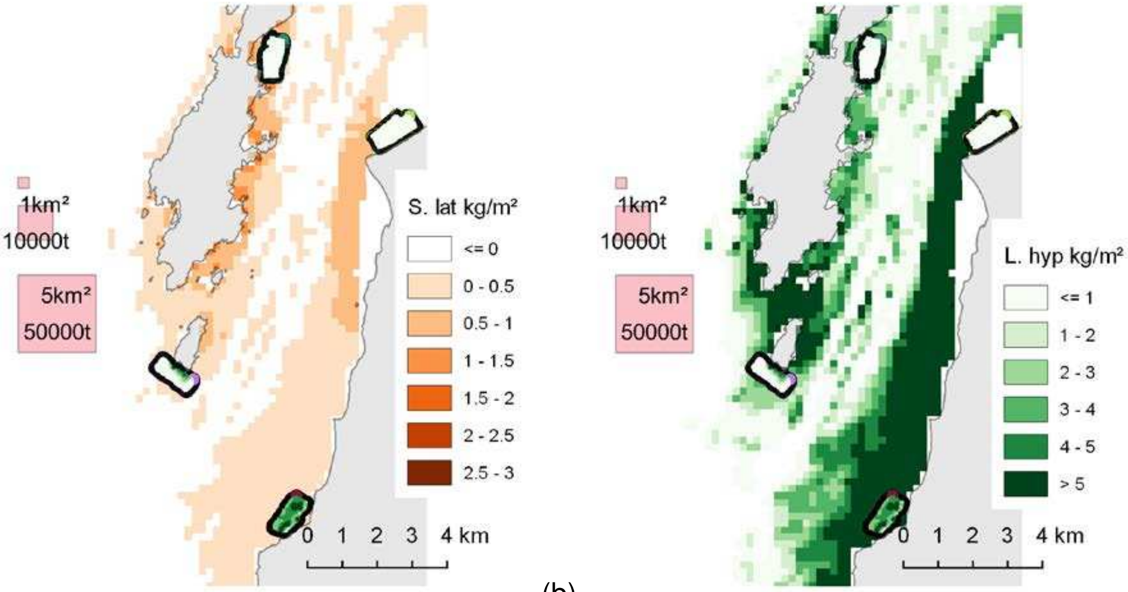
For the less-abundant species, furbellows *Saccorhiza polyschides* and oarweed *Laminaria digitata*, suitable habitats are more evenly spread around Scotland (Figure 4), but the largest areas remain in the Outer Hebrides, Orkney and the Minch. Patterns generally follow the distribution of suitable habitat conditions for each species, particularly the association of *Saccorhiza polyschides* with intermediate wave exposure.

Given the direct use of MNCR survey data in the statistical models used in its production, this map may be considered with a greater degree of confidence than that for projected biomass, with the latter built on the combination of predicted habitats and assumptions about scaling of biomass to abundance (See Annex A for more details.)

2.3.1 Scotland-wide kelp biomass estimation

Biomass scales for converting probabilities of abundance category based on population densities (Annex A, Table A1) can be used to estimate biomass over the whole region and for specific areas for those species for which plant sizes are known. These projections have therefore been done for *Laminaria hyperborea* and *Saccharina latissima* using data on plant sizes and densities collected during this project, and for *Saccorhiza polyschides* and *Laminaria digitata* using published values for average biomass per unit area. Countrywide-scale estimates of biomass should be considered in the light of caveats around the data, particularly the lack of information on suitable bottom types (solid bedrock, boulders etc.), and unquantified uncertainty in biomass-scaling parameters to get a good local fit to observed biomass in areas of known kelp habitat.

Higher-resolution models at the scale of locally identified areas of kelp beds, in areas of potential harvesting, should give more realistic estimates of biomass at the scale needed to manage harvesting activities. Around Gigha (Figure 5; see also Section 4), the large-scale model indicates those places where threshold levels of biomass suitable for harvesting may occur, although a properly validated higher-resolution model (at 10m scale as in Bekkby *et al.*, 2009) would provide much more accurate estimates. In Figure 5 predicted kelp biomass is only displayed for *Laminaria hyperborea* and *Saccharina latissima*, because these were the only kelp plants identified from the survey work.



(a) (b)

Figure 5. *Predicted kelp biomass density around Gigha for (a)* Saccharina latissima *(using biomass scale 3 from Annex A; Table A1) and (b)* Laminaria hyperborea *(using biomass scale 2 from Annex A, Table A1).*

Using the methodology so far developed, total biomass has been predicted for *Laminaria hyperborea, Saccharina latissima*, *Saccorhiza polyschides* and *Laminaria digitata* across the modelled area of Scotland, in those places being less than 5 km from the shoreline and not adjacent to areas of intertidal soft sediment. Scotland's Marine Atlas (Baxter *et al*., 2011) divides the areas around the coast into 10 regions (Figure 6) allowing the 200 m-scale model estimates of biomass to be aggregated into convenient units. Values are presented here for total biomass, including all biomass values no matter how small, and as totals for those areas where biomass exceeds 2 kg/m^2 and 5 kg/m^2, representing those kelp beds where biomass density is more likely to support an economical harvest. Since these biomass estimates are directly linked to habitat suitability, the patterns among 20 km boxes (Figures 7-8) follow those for predictions of areas of kelp habitat). Total biomass of *Laminaria hyperborea* was predicted to be 19.7 Mt wet weight, with 15.5 Mt in a total area of 3,747 km^2 where biomass density exceeds 2 kg/m^2, and 6.8 Mt in an area of 1,103 km^2 where biomass density was predicted to be greater than 5kg/m^2. With a lower biomass density scaling factor, *Saccharina latissima*, was predicted to have a total biomass of 2.5 Mt across Scotland, but in negligible quantities above 2 kg/m^2.

The region with the most *Laminaria hyperborea* was the Minch and Inner Hebrides with 35% of the biomass in areas >5 kg/m^2, followed by the west coast of the Outer Hebrides (21%), the North Coast and Orkney (20%), and the combined east and west coasts of Shetland (10%).

Saccorhiza polyschides (furbellows) and *Laminaria digitata* (oarweed) were predicted to have approximately 100 times less biomass than *Laminaria hyperborea* (Table 4, Figures 9-10). This is due to the combination of the much reduced prevalence of these two species in the diver surveys around Scotland and the smaller biomass per unit area in dense stands where these species have been quantified elsewhere (Annex A).

Table 4. *Predicted biomass of kelp species in Scotland's Marine Atlas Regions. Values calculated from habitat suitability modelling using biomass densities corresponding to categorical (SACFOR) abundance scales (*Laminaria hyperborea*: S, 25kg/m^2; A, 25kg/m^2; C, 0.83; F, 0.083, O, 0.0083; R, 0.0016;* Saccharina latissima*: S, 6kg/m^2; A, 6kg/m^2; C, 0.2; F, 0.02, O, 0.002; R; 0.0002;* Saccorhiza polyschides, Laminaria digitata: *S, 3kg/m^2; A, 3kg/m^2; C, 0.3; F, 0.03, O, 0.003; R, 0.0003). No predicted areas exceeded the 5kg/m^2 threshold for* Saccharina latissima.

	Total modelled *Laminaria hyperborea* biomass (1,000t)	Total modelled *Saccharina latissima* biomass (1,000t)	Total modelled *Saccorhiza polyschides* biomass (1,000t)	Total modelled *Laminaria digitata* biomass (1,000t)	*Laminaria hyperborea* biomass >2kg/m² (1,000t)	Area >2kg/m² (km^2)	*Laminaria hyperborea* biomass >5kg/m²	Area >5kg/m² (km^2)	%
(out of area)	760	34	2.9	4.3	555	128	303	50	4%
West of Outer Hebrides	3,011	185	19.3	24.5	2,511	542	1,438	225	21%
Minch and Inner Hebrides	7,746	1,055	68.4	82.8	5,996	1,503	2,346	388	35%
North coast and Orkney	3,529	501	46.6	18.4	3,024	719	1,335	216	20%
West Shetland	772	173	17.2	6.2	627	135	367	60	5%
East Shetland	753	144	16.4	3.8	626	144	318	53	5%
Moray and Caithness	1,103	78	5.6	4.8	835	196	376	60	6%
East Scotland Coast	724	35	2.9	3.0	569	130	294	48	4%
Clyde Sea	801	201	4.1	8.8	492	146	92	16	1%
Solway and North Channel	852	52	6.0	6.7	547	144	158	27	2%
Forth	443	40	1.3	2.1	312	88	60	10	1%
Totals (1,000t)	19,734	2,463	188	161	15,539	3,747 (km^2)	6,783	1,103 (km^2)	
(Mt)	19.73	2.46	0.19	0.16	15.54		6.78		

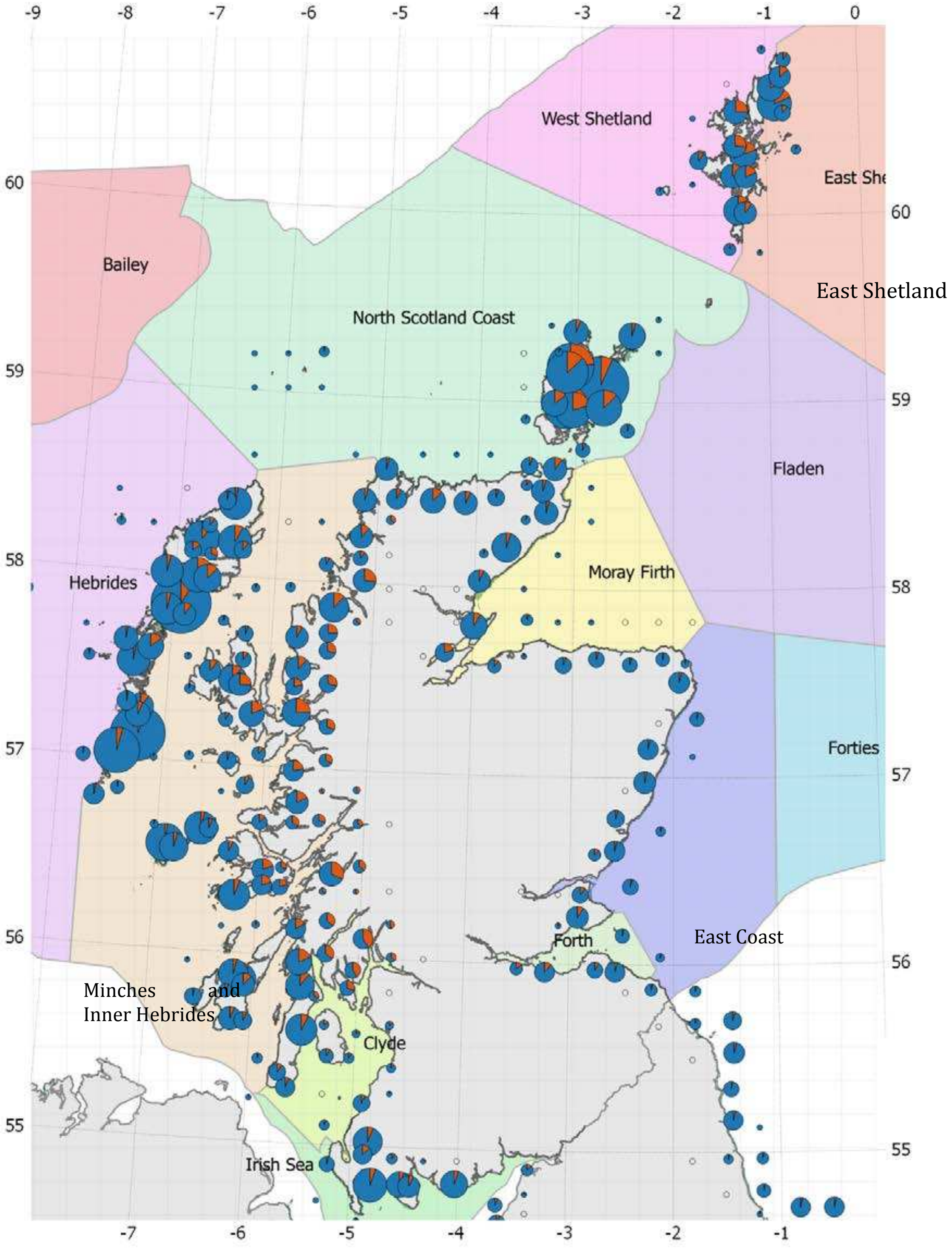


Figure 6. Patterns of predicted kelp biomass across Scotland. Pies show the relative proportions of the total biomass of Laminaria hyperborea *(blue) and* Saccharina latissima *(orange) combined in 20km grid squares, with the size of the pie charts scaled to the total biomass of both species.*

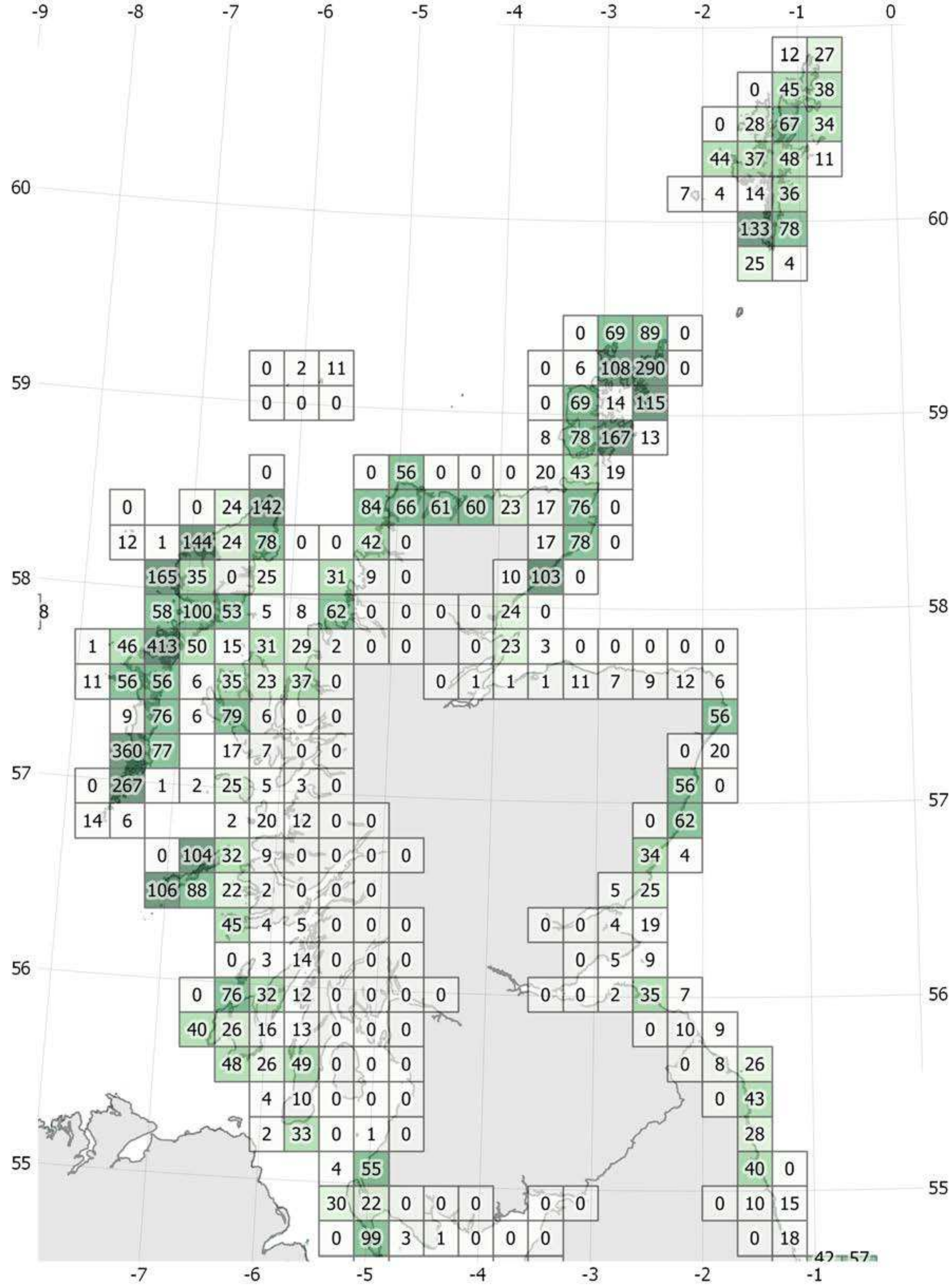


Figure 7. *Predicted biomass of* Laminaria hyperborea (*in 1,000 tonne units) in areas of harvestable densities (>5 kg/m^2) by 20 km grid squares around Scotland.*

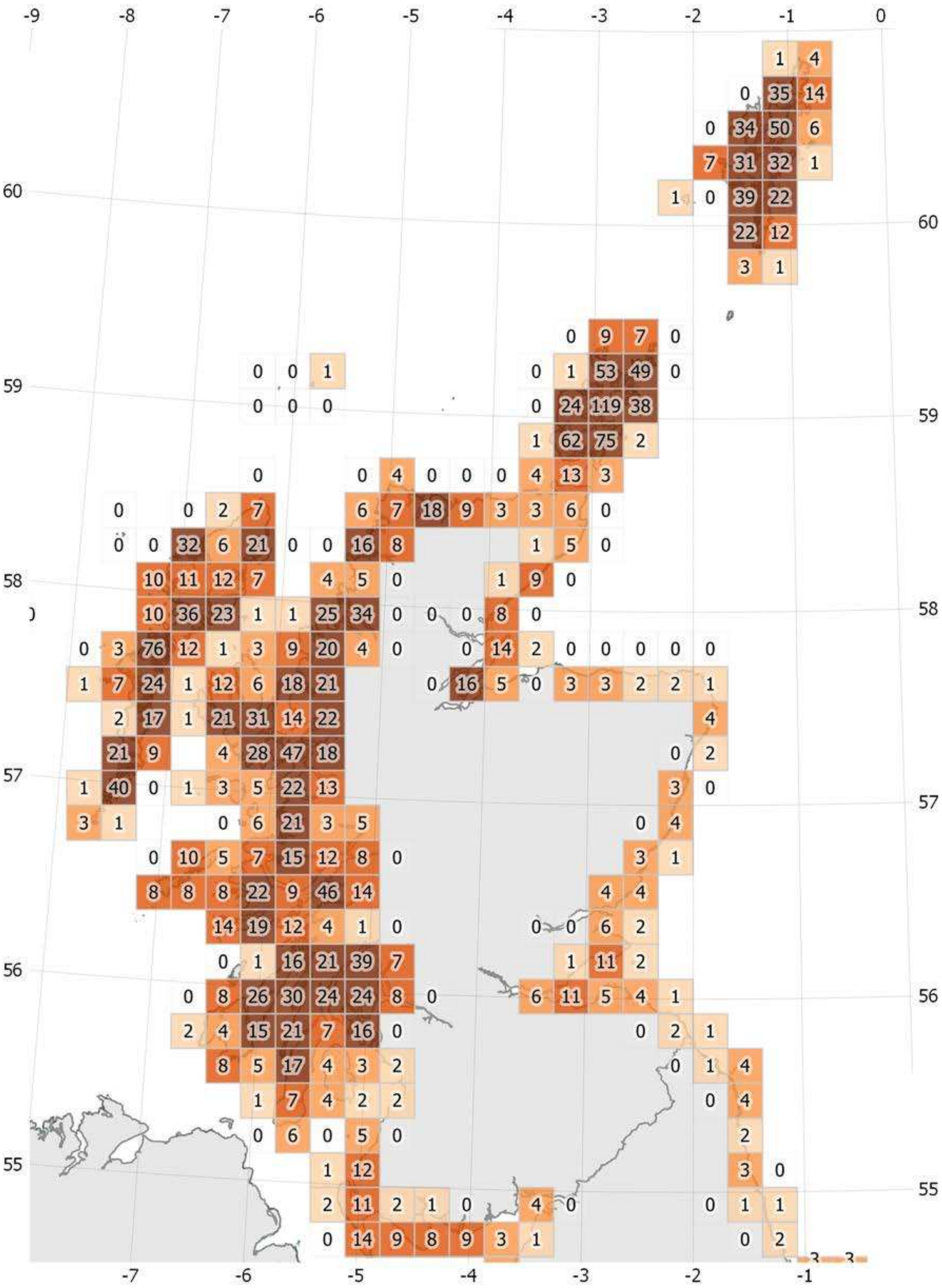


Figure 8. *Predicted biomass of* Saccharina latissima (*in 1,000 tonne units) across all biomass densities by 20 km grid squares around Scotland.*

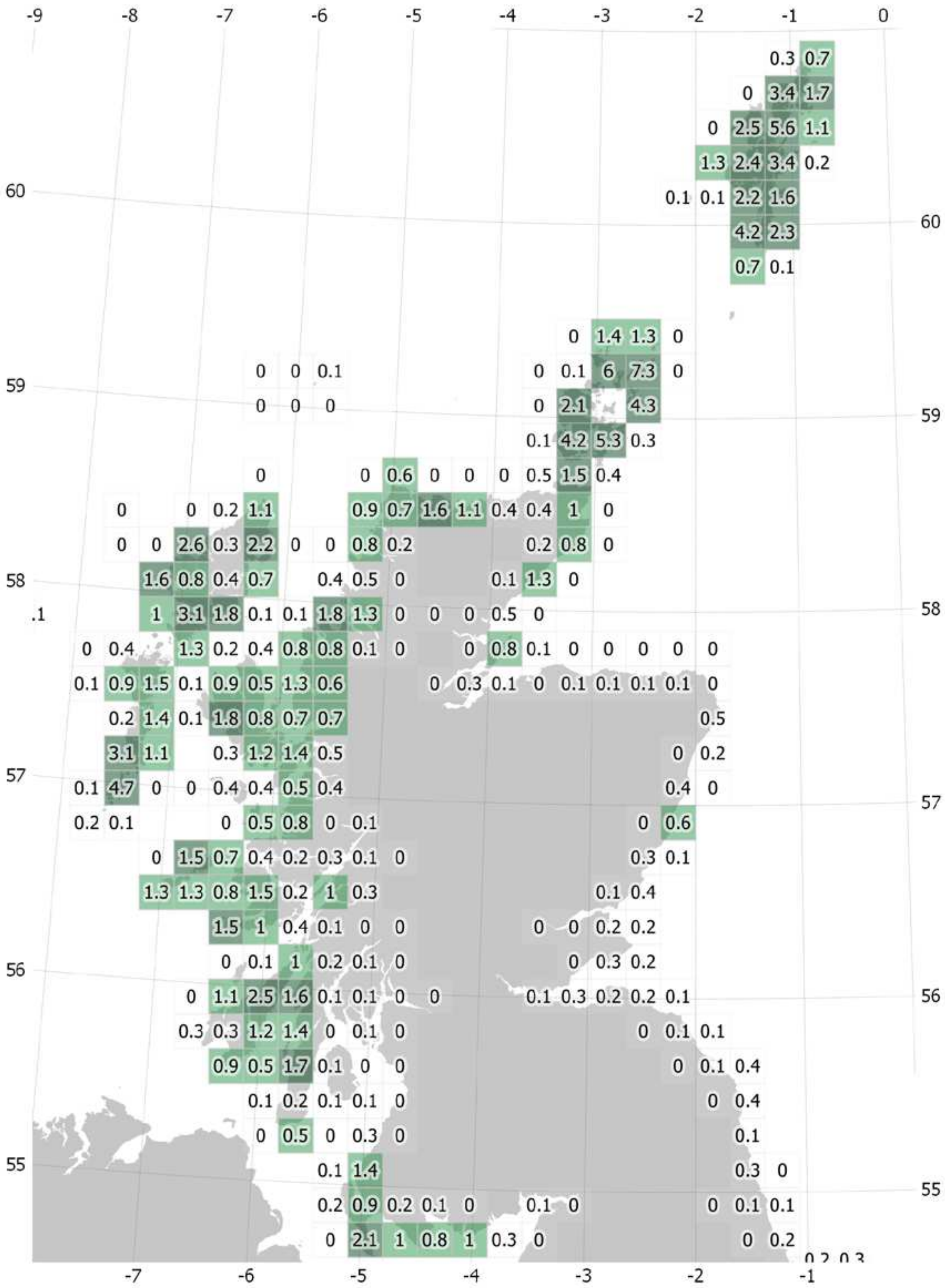


Figure 9. *Predicted biomass of* Saccorhiza polyschides (*in 1,000 tonne units) across all biomass densities by 20 km grid squares around Scotland.*

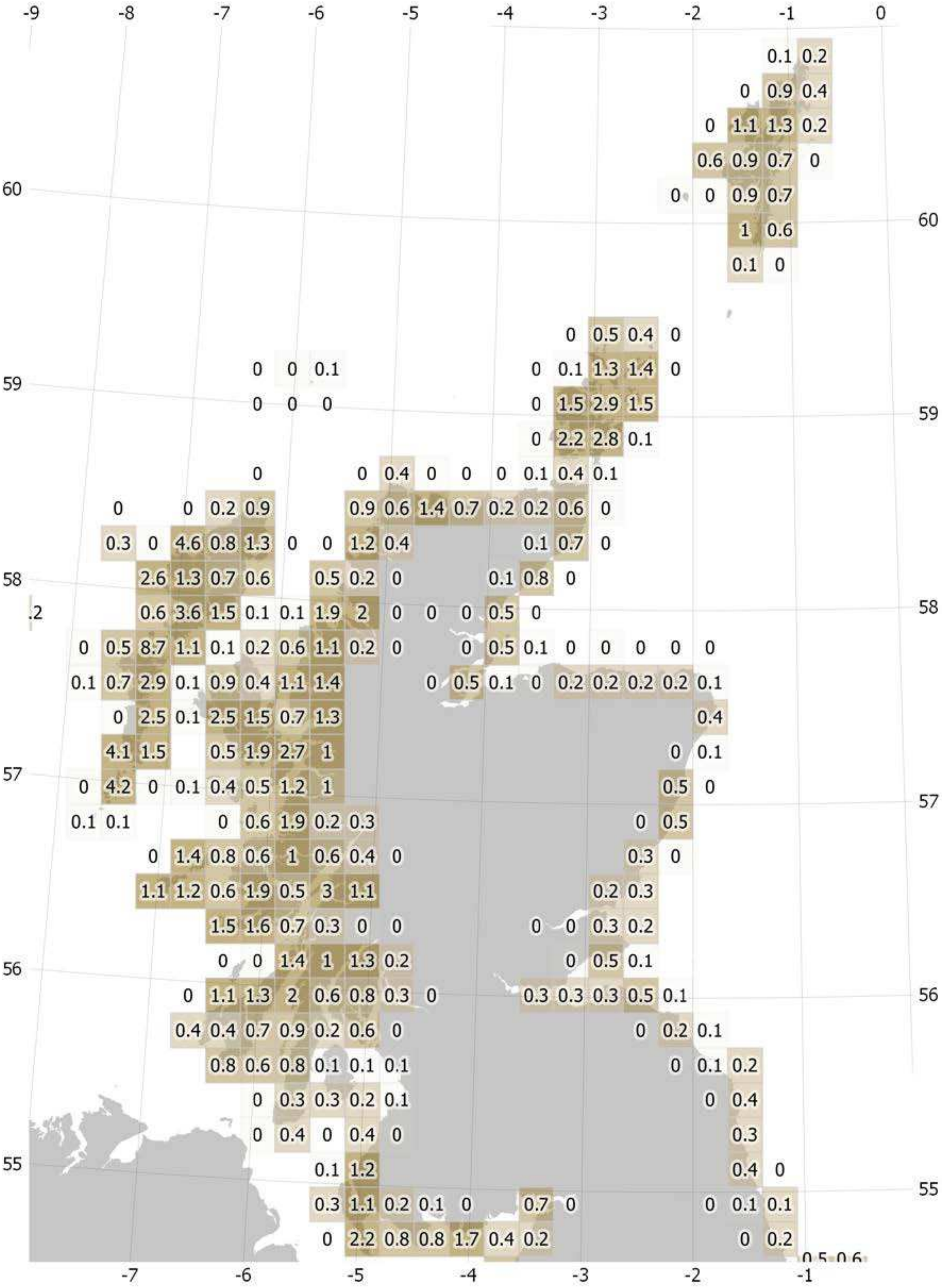


Figure 10. *Predicted biomass of* Laminaria digitata (*in 1,000 tonne units) across all biomass densities by 20 km grid squares around Scotland.*

At the 20 km scale, areas emerge as likely candidates for high yielding harvesting areas (Figures 7-8). 20-km boxes with more than a predicted total of 50,000 t of *Laminaria hyperborea* at a biomass density >5 kg/m^2 appear from the Mull of Galloway, Girvan, Gigha, Colonsay and North Islay, Coll and Tiree, North Skye, west and east coasts of the Outer Hebrides, northwest mainland Scotland, and all around Orkney and Shetland. Along the east coast, localised high kelp biomass areas are predicted north and south of Aberdeen (Figure 7). For sugar kelp, *Saccharina latissima*, no areas were predicted to have an average of over 2 kg/m^2, but habitat suitable for substantial populations was predicted in the protected waters of the west coast sea lochs and the firths and voes of Orkney and Shetland (Figure 8).

Saccorhiza polyschides (furbellows) and *Laminaria digitata* (oarweed) were predicted to have up to 7,000 t and 5,000 t per 20 km box, but more typically a few hundred to 1,000 t per box. Geographical patterns largely followed those of the two more abundant kelp species. With such smaller stocks, it is unlikely that these two species would be targeted for harvesting, and much more likely that any harvested material would be a by-catch of attempts to harvest *Laminaria hyperborea* or *Saccharina latissima*.

In order to make some of the outputs of the modelling accessible, a supplementary 'Kelp Atlas' document has been created as part of this project (Burrows & Allen, 2018). For this Kelp Atlas, the coastline of Scotland has been divided into 49 x 50 km squares. Each of these 50 km squares is displayed as a zoomed in map for the four kelp species examined during the project, showing where the model predicted habitat suitable for that specific kelp species to grow.

2.3.2 Seasonal variation in kelp biomass

Without specific data on changes in harvestable biomass over time, the projected biomass values represent average conditions. In *Laminaria hyperborea* the main growth of the lamina (the flat blade of the plant) is between February and May, with relatively little change at other times (Kain, 1979). Laminarians are effectively deciduous, with the previous year's growth shed from the end of the growing lamina during the rapid growth phase. Plants are perennial, living for 10 years or more, with the annually renewed lamina forming between 40% and 80% of the total weight of the plant (see Annex A, Figure A6), and the perennial stipe 20% to 60% of biomass. Given that the latter is present all year round, and lamina growth rapidly replaces shed material, the seasonal variation in biomass is likely to be small relative to the total harvestable biomass. The most extreme seasonal variation is seen in furbellows *Saccorhiza polyschides* with whole kelp plants largely absent in winter.

2.4 Comparison with Existing Estimates of Scotland's Seaweed Biomass

These predicted regional patterns are very similar to the early estimates made from surveys in the 1940s and 1950s by the Institute of Seaweed Research (ISR) (Walker, 1954). The ISR surveys produced an estimated total biomass of *Laminaria hyperborea* of 10 Mt, with 3 to 4 Mt concentrated in "quantities of potential economic value". Values produced in this report (20 Mt, with 7 Mt in areas above 5 kg/m^2) are approximately twice the historical estimates. A reason for this discrepancy is that the spring-grab based biomass density estimates of the ISR surveys were likely to be an underestimate of the actual biomass, since the spring grab was not 100% efficient in sampling kelp plants. Later researchers using SCUBA (Kain, 1979) directly sampled plants on the seabed and produced much higher biomass densities, up to the 25 kg/m^2 maximum used here to convert habitat suitability to biomass.

One important aspect of the ISR surveys is the revealed magnitude of annual variation in biomass. Yearly surveys of the entire coastline showed that average biomass of *Laminaria hyperborea* around Scotland varied from 7.2 kg/m^2 in 1947 to 1.5 kg/m^2 in 1953 (Walker, 1956b). While unlikely to be related to sunspots as originally suggested, this magnitude of interannual variation has important consequences for a potential harvesting industry. While the 10-year record is much too short to determine associations with any statistical confidence, the year-to-year changes are positively correlated with the North Atlantic Oscillation (NAO) in June of the previous year (meaning wet, windy summers), and negatively correlated with NAO in October of the previous year (dry, settled autumns). Weather patterns and related climatic factors are likely to have driven the changes, and are likely to drive similar changes in the future. The consequence for a harvesting industry that needs to maintain an annual harvest of a given size is that greater areas will be needed for harvests in low-biomass years.

2.5 Discrepancy and Uncertainty in Model Predictions

As Section 2.3 shows, the ability of the kelp habitat-suitability model to produce predictions of biomass of *Laminaria hyperborea* that match locally measured or estimated values is limited. It must be recognised that kelp habitat surveys made in this project (Section 2.6) and taken from the literature by Kain (1977) were in areas of known kelp habitat. The kelp habitat-suitability model includes prediction of the likelihoods of not finding kelp (P(Abundance)< “Rare”). The model fitted best when the biomass of kelp at the higher abundance categories was increased to very high levels (25 kg/m^2). In areas where there was a 50% likelihood of finding kelp at least Abundant (>1 plant per m^2), the effect of the alternate 50% likelihood of kelp being less than Abundant reduced the final predicted biomass value to half the maximum value (25 kg/m^2).

The main purpose of this scale of model is well served in identifying those areas where large stocks of kelp are likely to be, as identified by those combinations of environmental factors that are associated with high abundance values in the MNCR surveys. Uprating the biomass conversion scales to better match observed biomass values in areas of known kelp habitat may be appropriate for that purpose, but carries a risk of overestimating kelp stock size at the landscape scale, since the targeted surveys ignore areas with no kelp. A recommendation here is that use of biomass scaling with a habitat suitability model like this one should be constrained to predicting kelp biomass in areas of known kelp habitat, and that a more conservative (lower biomass, reflecting observed percent cover / density scaling) scaling factor should be used to estimate seaweed stock sizes in broader areas where areas of kelp habitat have not yet been identified through surveying.

2.6 Site Surveys in Areas Selected for Suitability for Kelp Harvesting

Initial consideration of the earlier surveys (Walker, 1954) and more recent modelling studies (Burrows *et al*., 2014a) suggested three major areas for surveys of areas with potentially harvestable quantities of kelp: (1) Kintyre around Gigha, (2) Skye, and (3) Orkney. These areas were selected to give representative sites for kelp in high-yield areas. Boat-based surveys were planned to deploy single beam acoustic sensors and seabed cameras to give the type of intensive coverage of areas needed to assess the exploitable biomass of kelp in those areas. Diver surveys were necessary to calibrate the acoustic method of kelp estimation recommended by our subcontractor Envision for use in kelp assessment (Blight *et al.*, 2011) and to provide important validation of predicted kelp abundance from the large-scale model. Acoustic surveys were planned to cover an area of 1.2 x 0.5 km in one exposed and one sheltered location in each region, with diver surveys made in two of these four areas.

2.6.1 Acoustic / camera surveys

Envision used two survey personnel at the three proposed locations to deploy acoustic and positioning equipment on a vessel of opportunity. After calibrations and checks, acoustic data were gathered in a series of survey lines over a day at each location. The equipment used the SonarPro software package with a Simrad ES60 dual frequency fisheries sounder and a Simrad 38/200 Combi D transducer (38 kHz and 200 kHz). The program detects the echo intensity between the seafloor and the top of the vegetation, and uses consecutive ‘pings’ to estimate area and volume inhabited by algae. Outputs are depth, height of kelp canopy, signal strength under the canopy, percentage area (PAI) and percentage volume inhabited (PVI). Spatial analysis was used to interpolate between each point giving grid coverage. Mapped echogram data were validated using underwater cameras deployed during a 1-day survey of each site, giving density and biomass measurements to relate to acoustic measures, and enabling biomass and distribution to be mapped. Short (2-5 mins) tows were located using a dGPS system for vessel positioning to 1 metre accuracy. Scale bars or laser pointers provided a scale for camera images. Analysis of video images confirmed the composition and identity of algal species present and measures of biomass.

The detailed methods and outcome of this work are presented in Annex B, which includes a report from Envision on their field survey, covering methodologies and data acquired. The data from Envision were integrated into the model interpretation as described in Section 2.7 below.

2.6.2 Diver surveys

Harvestable biomass and plant density were measured at candidate harvesting areas to establish how seabed cover from model predictions, observations from acoustic surveys and cameras can be transformed into estimates of yield on larger scales. Divers quantified kelp biomass and density along gradients of depth and wave exposure. At each survey site, divers recorded the percentage cover and density of mature kelp plants in 1 m^2 quadrats in areas of maximum kelp density from 2 m to 5 m below chart datum. Kelp plants within the quadrats were also collected for size measurements: fresh weight per plant and per m^2, the weight and length of the stipe and the lamina, the age of the plant, and composition in terms of alginate, total sugars and ash/dry weight (Schiener *et al.*, 2015) (although results of these analysis remain incomplete at the time of writing in November 2017). The kelp measurements were compared with model predictions to validate the predictive spatial models (see Annex A), which is a successful approach used in assessment of kelp in Brittany (Méléder *et al.*, 2010).

2.7 Integrating Site Survey Information and Modelled Outputs

The data from models and the acoustic, video and diver surveys (Annex B) can be cross-referenced to give a broader picture of the kelp resource around Scotland (Figure 11). For the two selected for which acoustic surveys were completed, it can be seen that the areas predicted by the model as having at least some kelp present are more extensive than those shown by the acoustic surveys. This mismatch does not reveal a required refinement of the model, but does show that surveys of a higher resolution than the model show patterns not predicted by the lower resolution model. The mismatch also highlights the need for much better information on substratum type. Areas shown not to have abundant kelp where environmental conditions were otherwise suitable, such as on the Kintyre coast east of Gigha (Figure 11b) were generally those lacking suitable hard substrata for the attachment of kelp plants. It must therefore be recognised that the definition of kelp habitat as where some kelp is more than likely to be present is much broader than that of where harvestable quantities of kelp may be present (dependent on methods of harvest, distance to port and the vessels and harvesting equipment available). However, the consistency of the surveys in finding kelp where expected and general agreement among the methods supports the multiscale approach adopted here. Validation of model predictions with acoustic and video survey data by comparison of the 200 m scale model with the diver data (see Annex A) suggests that the fit to smaller scale patterns may be improved by better information on the drivers of abundance at these scales.

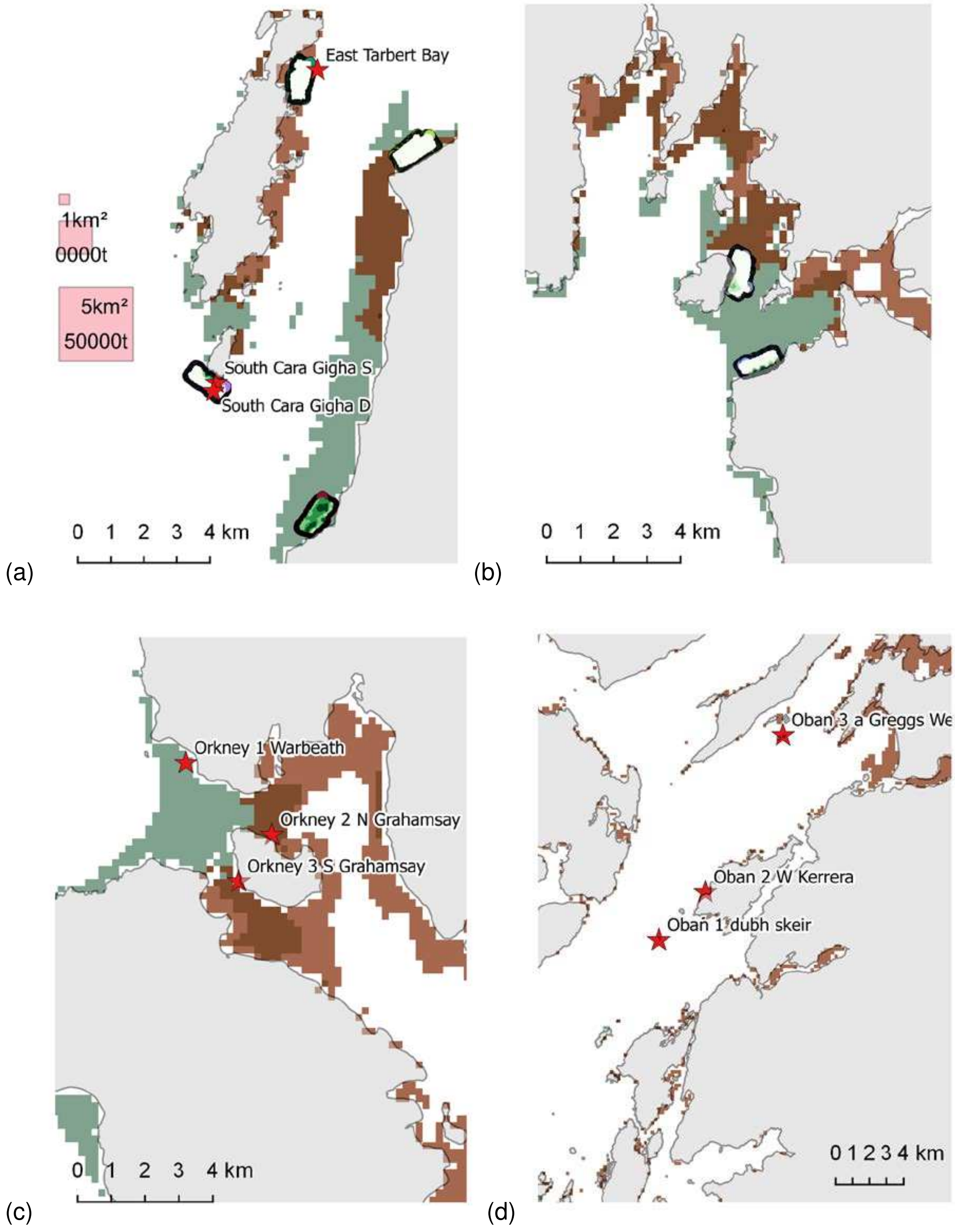


Figure 11. *Predicted kelp habitat (green,* Laminaria hyperborea*; light brown,* Saccharina latissima*; dark brown, both), acoustic and video surveyed areas (black outlined patches) and diver surveys (red stars) in the three areas surveyed in this project (a) Gigha, (b) Skye, (c) Orkney; and additional sites previously surveyed around (d) Oban.*

2.8 Harvesting Site Constraint Analysis

The predictive modelling undertaken as described above provides one layer of information to identify optimum locations for kelp harvesting, that being where there is potential for kelp biomass to be present. However, there are a number of additional factors that need to be considered when considering whether a particular area is suitable for kelp harvesting, such as the presence of protected areas, distance for landing ports etc. Depending on the outlook of the parties looking at 'optimum' harvesting locations, there is likely to be a difference in how much weighting particular spatial data is given with regards to how important it is perceived. So whilst areas such as the Minch, Inner Hebrides, the west coast of the Outer Hebrides, the north coast, Orkney and Shetland may be regarded as optimal locations in terms of available biomass, there may also be significant constraints found within them that requires consideration at both a strategic and project level. Table 5 below outlines the factors that may constrain the suitability of areas of kelp harvesting.

Table 5. *Summary of constraints that may limit potential kelp harvesting locations*

Constraint	Rationale	Notes
Kelp distribution	Harvesting needs to target areas of sufficient kelp biomass	See Section 2.3 of this report Kelp Atlas supplementary document (Burrows & Allen, 2018)
Designated natural conservation features	The boundaries of designated conservation areas (e.g. MPAs, SACs, SSSIs, SPAs) may overlap or be adjacent to kelp habitat. Depending on the habitats/ species designation for each area, there may be concern over impacts from kelp harvesting on the health of these features	See Section 3.8 of this report for overlap between kelp habitats and PMFs
Landing sites	The distance to suitable landing points for harvested kelp may limit which areas can be realistically harvested	See Section 6.2 of this report. May be mitigated at additional cost to operator if infrastructure developed at specific locations
Maritime Heritage	The presence of wrecks and other maritime cultural heritage features on the seabed may prevent harvesting of kelp	
Navigational lanes	Ensuring the safe passage of vessels may mean that safe harvesting activities are not possible in certain areas	

Constraint	Rationale	Notes
Infrastructure	The presence of seabed infrastructure such as telecommunication cables and pipelines may be a barrier to kelp harvesting	
Commercial fisheries	Where specific areas of kelp habitat are a focus of commercial fishery activity, it is unlikely that kelp harvesting would be viewed favourably	See Section 3.10 of this report
Soft sediment coastline	Kelp habitats provide a potential protective barrier to hydrodynamic processes eroding soft sediment coasts. Loss of kelp may leave these coastlines vulnerable, particularly to any extreme weather events.	

It should be noted that the table above may not be a comprehensive list of potential constraints; engagement with the Regulators and stakeholders for specific sites may highlight additional areas of concern. Early engagement with these groups is essential to understanding potential constraints that may reduce the total amount of kelp harvestable in a given area, and thus is to the harvester's advantage. The spatial mapping of these constraints is beyond the scope of this current project. Data layers that show the geographical spread for many of these factors can be accessed and downloaded via the Marine Scotland National Marine Plan Interactive website (https://marinescotland.atkinsgeospatial.com/nmpi/).

Some constraints may result in areas being considered 'unavailable' for harvesting activities. Examples of this would include areas where coastal erosion has been highlighted as a concern (e.g. Outer Hebrides), or where archaeological features such as wrecks are present on the seabed. Seabed obstacles such as wrecks would not only halt activities due to potential risk to historic and heritage features, but also because they could potential damage and entangle harvesting equipment. As detailed in Table 5 above, constraints concerning overlap between kelp habitats and commercial fishing areas are examined in Section 3.10 of this report, whilst Section 6.2 looks at the logistical constraints based on distance between kelp habitats and landing ports. The overlap between kelp habitats and protected features is discussed further in Section 3.8.

Further discussion regarding constraint analysis at a strategic level is undertaken in Section 5.3.1 of this report where the management and planning of harvesting are looked at in more detail.

3 ECOLOGICAL IMPACTS OF KELP HARVESTING

To inform future assessment and management of kelp harvesting it is necessary to understand kelp ecology and the likely impacts of its removal on both the kelp and associated biota. Building on information in Scottish Government (2016), this section reviews these aspects.

3.1 Kelp Reproductive Biology

KEY POINTS

- **Kelp have a lifecycle that alternates between two stages, one being the large, visible kelp plant that is harvested, the other as microscopic reproductive spores (zoospores).**
- **For kelp to recolonise a cleared areas, there is a requirement for the successful transport of zoospores, which need to settle and grow to become mature kelp plants**
- **For *Laminaria* species, estimates of spore dispersal range from a few 10s of meters to 200 m; thus, harvested areas should probably be no more than 100 m away from intact populations of reproducing adult plants to avoid recolonization failure. Less than 100% extraction of plants from an area should ensure this occurs.**

All kelp species have a heteromorphic life cycle (i.e. occurring in two or more different forms at different stages in the life cycle; see Figure 12) with alternating phases of a macroscopic, asexual, diploid sporophyte (i.e. visible kelp plant) and a microscopic, sexual, haploid gametophyte (Wilkinson, 1995; Hurd *et al.*, 2014). The heteromorphic life history has implications for the colonisation and persistence of kelp populations, and they are therefore not analogous to terrestrial seed-producing plants (Schiel, 2006). The different life stages of kelp must survive multiple hazards, which vary depending on the exact phase of the lifecycle (Table 6).

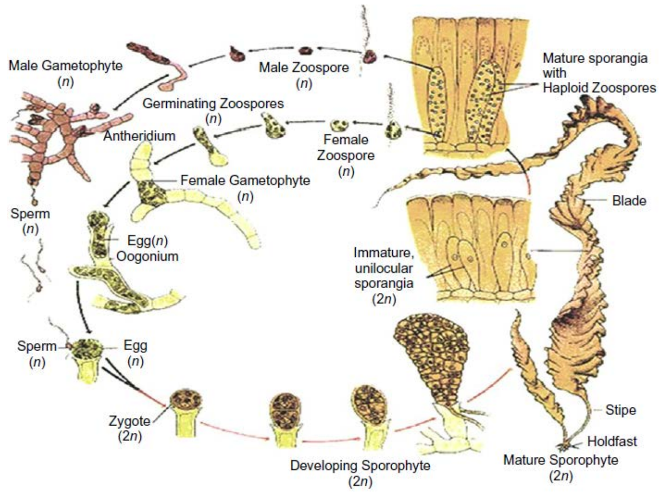


***Figure 12.** Life cycle of* Laminaria *(read in an anti-clockwise direction) (Kim & Bhatnagar, 2011)*

Table 6. *Natural hazards to different stages of the kelp life-cycle (modified from Figure 2.5 in Hurd* et al., *2014).*

Stage	Hazards
Adult plant	Removal by storms Being overgrown or shaded although less risk once plants are large Being grazed Being infected with a disease Being damaged by parasites
Zoospores	Being eaten by planktonic predators or filter feeders Failing to find suitable substrate to settle on Being inhibited by chemicals released from other species
Gametophyte	Being overgrown or shaded by other species Being grazed Being buried or abraded by sediments
Sperm	Failure to locate and fertilise an egg while viable
Microscopic sporophyte	Being overgrown or shaded Being grazed Being buried or abraded by sediments
Juvenile plant	Being overgrown or shaded Being outgrown by conspecifics or competing species Being grazed

The general reproductive periods for European kelps are September or October-April for *Laminaria hyperborea* (Fredriksen *et al.*, 1995; Kain 2009) with the other species (*L. digitata, Saccharina latissima, Saccorhiza polyschides, Alaria esculenta*) tending to reproduce in the autumn through early winter.

Within the late summer / autumn reproductive season, *L. digitata* shows two phases of fecundity, one in June/July and another in October/November, which results in two pulses of recruitment, one in October/November and the other in March-May. Recruits derived from spores released in the autumn have a significantly faster growth rate compared to those derived from spring spores (Pérez, 1971). The differences in growth are related to light availability which is affected by the amount of shading from older plants at the different times of the year. For this reason, manual harvesting of *L. digitata* was traditionally carried out in autumn, when it was easier to pull plants from the substratum. As a consequence of the decreasing adherence of the holdfast, whole plants often get dislodged during autumn and winter storms and in unexploited conditions the overall annual mortality can be up to 50% (Pérez (1971) and Arzel (1989) cited in Werner & Kraan, 2004).

While the mechanisms of reproduction are similar for all members of Laminariales, the structure of the reproductive organs (the sori from which the haploid zoospores are released) varies between species (Werner & Kraan, 2004). Such structural differences in the reproductive organs are important, since the height of removal will have different implications on the species. In *S. polyschides* and *A. esculenta* the reproductive organs develop at the base of the stipe and so reproduction will still take place if the blade is removed. In contrast, the opportunity for reproduction is lost in *Laminaria* species when the blades are removed.

Recolonisation of harvested areas of *Laminaria* species thus needs to rely on the transport of zoospores from adjacent unharvested areas.

The dispersal range of the spores is of importance in understanding the regeneration of harvested areas and in determining the width of cut swathes. Kelp spores only remain in the water column for around 24 h and their dispersal range is generally thought to be of the order of tens of metres from the source (Chapman, 1987). Early studies on *A. esculenta* and *Macrocystis pyrifera* reported dispersal ranges of < 10 m (Fredriksen *et al*., 1995) but studies on the dispersal of *L. hyperborea* spores in Norway suggested distances of at least 200 m from the parent plant (Fredriksen *et al.,* 1995). The dispersal capability of the zoospores will be affected by the species, release depth (partly linked to where on the plant the sporophylls or sori are located) and local hydrographic conditions.

Kelp zoospores possess flagella, allowing limited swimming. Although this probably has little impact on their dispersal potential, it helps the spores locate suitable settling sites (Amsler *et al*., 1992). After settlement the spores germinate (Kain & Jones, 1964) but a period of dormancy may then follow until light levels increase in early spring when the benthic gametophytes finish their vegetative growth phase and become fertile.

For successful fertilisation female and male gametophytes must be close (within a few mm) to each other. Fertilisation is synchronised by a combination of environmental factors and the egg releases a pheromone, which triggers the release of spermatozoids. After fertilisation, the sporophyte starts to develop and will eventually become a mature plant.

3.2 Kelp Growth

KEY POINTS

- **Kelp are important primary producers in inshore areas and the plants exhibit seasonal growth patterns which need to be taken into account when planning harvesting schedules.**
- **Growth of kelp can be variable depending on local conditions so one must be cautious when using average production values derived from large areas in calculating potential harvest rates.**
- **Inter-annual variability in kelp biomass can be up to five fold. Such variability would impact harvest yields and the area requiring to be cut in any particular year to achieve a certain yield.**

Within marine ecosystems kelp have potential high productivity (Westlake, 1963) but net production varies with species, depth and location (Sjøtun *et al.*, 1993). Total primary production from kelp beds around Scotland was considered in recent reviews by (Smale *et al.,* 2013a) and (Burrows *et al.*, 2014a).

Kain & Jones (1977) estimated annual growth of *L. hyperborea* as low as 0.4 kg C m^{-2} y^{-1}. This value compares with earlier estimates of 0.39 – 0.53 kg C m^{-2} y^{-1} based on spring-grab sampling around Scotland (Westlake 1963); as high as 1.3 kg C m^{-2} y^{-1} from Sennen Cove, Cornwall (Whittock 1969); production of the lamina of 0.67 kg C m^{-2} y^{-1} (at 3 m depth) – 0.31 kg C m^{-2} y^{-1} (at 9 m depth) plus a further 0.14 kg C m^{-2} - 0.057 kg C m^{-2} for stipe growth (Jupp & Drew, 1974). Other estimates of productivity for this species from other locations (St Abbs and Helgoland) are given in Jupp & Drew (1974), and range from 0.43 to 0.99 kg C m-2 y^{-1}. Productivity values are also influenced by the methodology used and by assumptions concerning conversions between dry weight and carbon content. For example, Jupp & Drew (1974) suggest that the estimates in Westlake might be biased downwards because of the spring-grab method used to estimate the standing stock. Kain & Jones (1971) also suggested that growth rates of *L. hyperborea* in the Isle of Man were very similar to that found in some sites in Norway.

Using radiolabelled carbon uptake Johnston *et al.* (1977) estimated annual net production of *Saccharina latissima* (*Laminaria saccharina*) in Loch Creran, Scotland to be 68 g C y^{-1} per frond. Peak carbon fixation was between April to late July but a positive carbon fixation was found throughout the year. Taking account of the density of plants they estimated annual production to be around 0.12 kg C m^{-1} yr^{-1}.

Kelp consists of a blade (lamina), a stipe and a holdfast. The holdfast is an anchor and is not involved in nutrient uptake. The major zone for growth is called the meristem, which lies between the stipe and the lamina, where new tissue is continuously produced (Kain & Jones, 1963a). Although the main site of new tissue formation is the meristem, growth also occurs in the lamina contributing to increases in blade width and thickness (Kain & Jones, 1976a).

The annual cycle of growth varies with species. *Laminaria hyperborea* is a perennial where the lamina is shed in late spring and renewed over the following months. Blade regeneration takes between 5 – 10 months (Scottish Government, 2016). Other species of *Laminaria* spp. retain the blade adding new tissue at the basal meristem whilst losing older tissue at the tip through erosion. Although in older plants a balance is attained between production of new tissue and loss of old, the productivity contributes to the coastal marine food-web (see Section 3.3 on Secondary Production).

Growth in kelps is seasonal (Kain & Jones, 1963a; Lüning, 1979; Sjøtun *et al.*, 1993; Werner & Kraan, 2004). Highest growth usually occurs from early spring to late summer. In autumn growth rates decrease in order to build up carbohydrates reserves that are metabolised in late winter. This enables the perennial species to start growing early in the spring making them more competitive in comparison to those species, whose stimulus for growth depends on a higher level of irradiance, e.g. *S. polyschides*.

Kain & Jones (1976b) followed the growth of *L. hyperborea* on cleared substrate at different depths and reported that growth was maximal in Dec-June and declined in later summer. In *L. digitata and L. saccharina* in the southern North Sea growth declines at the end of summer but does not stop completely. In contrast, in *L. hyperborea* the high-growth period ends in late summer.

In Ireland growth of *L. digitata and L. hyperborea* follow similar trends with the maximum biomass being recorded in late autumn to early winter (Werner & Kraan 2004). Over winter biomass decreases due to dislodgement of whole plants but also losses of old tissue at the distal end of the kelp blades. There will also be some loss in weight due to the breakdown of metabolic reserves. In February, when growth starts again, a new meristem is activated below the old one, which leads to the distinctive lace-like form of the blade.

The timing of growth in *Laminaria* spp. seaweeds is controlled by an endogenous clock and so is not solely driven by seasonal changes in light, although seasonal changes in illumination entrain the clock and so act as a “Zeitgeber” (Lüning 1979; 1993; Schaffelke & Lüning, 1994).

In *L. hyperborea* the seasonal patterns of growth and the changing balance between total carbon content and stored carbohydrates also differ between mature and first-year plants (Sjøtun *et al.,* 1996). In particular, the young plants had a longer growing season whilst mature plants grew little during the summer and autumn. A similar finding of longer growing season in first-year plants was reported from Helgoland (Lüning, 1979).

The chemical composition of the plants also varies seasonally (Schiener *et al*., 2015). This can be an important consideration in terms of harvesting times - depending on the intended use of the harvested material.

Nutrient levels, especially availability of nitrogen, are another important factor controlling kelp growth (Gagné *et al*., 1982; Sjøtun *et al*., 1993). The availability of nutrients to the plants is related to the degree of water movement, especially later in the season, so that local hydrographic conditions are important.

Gagné *et al.* (1982) compared growth of *L. longicruris* at three sites in Nova Scotia which had varying seasonal nitrogen availability linked with oceanographic conditions. The varying nutrient availability affected the seasonal growth patterns. In nutrient limited situations, carbohydrates stored during the fast growth period are metabolised to sustain the plant. Interestingly transplantation experiments indicated that there might be some genetic differences between plants at different sites, suggesting possible adaptation to local conditions. However, this conclusion was refuted by Bolton & Lüning (1982) based on their results from incubating *Laminaria* spp. sourced from different locations at a range of temperatures. They suggested that the success of the kelps across a range of temperatures was the result of phenotypic plasticity rather than genetic adaptation.

Nutrient levels thus play a role in controlling net annual production with low annual productivity (0.12 kg C m^{-2} y^{-1}) being reported for *S. latissima* at a low flow, low nutrient site (Johnston *et al*., 1977).

3.3 Kelp as Contributors to Marine Foodwebs

KEY POINTS

- **Whilst some organisms do feed directly on kelp the main contribution to marine foodwebs is through detritus from blade erosion, fragmentation and dislodgement of whole fronds and thalli and the production of exudates.**
- **This detrital contribution can energetically subsidise consumers which are far from the kelp beds.**

Fresh kelp, even when fragmented, does not appear to be the preferred food source for most grazers (Christie *et al*., 2009; Yorke *et al*., 2013), although kelp may be selected in preference to seagrass (Doropoulos *et al*., 2009). The importance of kelp as a source of detritus has however been increasingly emphasised in recent decades (Krumhansl & Scheibling 2012).

Based on global studies, rates of detrital production from kelp blade erosion and fragmentation have been estimated to range from 8 to 2,657 g C m^{-2} yr^{-1}, and from 22 to 839 g C m^{-2} yr^{-1} from losses of fronds and thalli. Annual losses to detritus may be as high as 80% of production in un-harvested kelp beds (Krumhansl & Scheibling, 2012). As well as supporting adjacent communities, much of this material may be transported considerable distances from the kelp beds.

Although fresh kelp does not appear to be efficiently utilised by many marine organisms (Fredriksen, 2003), kelp produce large amounts of secretions which enter the dissolved organic carbon (DOC) pool in coastal waters. Johnston *et al.* (1977) studied productivity in *Saccharina latissima* (*Laminaria saccharina*) in Loch Creran, Scotland using radiolabelled carbon. Their results showed that about 40% of the gross fixed carbon is lost via distal fragments which enter the detrital pool. In addition, this species releases extracellular secretions representing up to 23% of gross carbon fixation (although this last figure was estimated rather than measured). Respiration accounted for about 37% of gross fixed carbon meaning that only a small proportion of fixed carbon is retained across the whole annual cycle. The actual rates of losses by secretion have been difficult to quantify although most sources suggest this is an important fate for fixed carbon contributing to the pool of dissolved organic carbon (DOC) in coastal waters. Exudates on the kelp surface (Laycock 1974) and DOC support microbial communities which in turn can be consumed by other organisms such as filter-feeding sponges, hydroids, bivalves, bryozoans, brittle stars, crustaceans and tunicates.

Kelp detritus is also broken down by microbes and this process can increase its nutritional value for consumers (Norderhaug *et al*., 2003). Studies of food-webs in kelp beds using isotope-ratios have suggested that kelp-derived material finds its way into the diets of a wide-range of organisms associated with the kelp beds including gadoid and non-gadoid fish and seabirds such as cormorants (*Phalacrocorax carbo*) and eider ducks (*Somateria mollisima*) (Fredriksen, 2003).

Kelp may thus support consumers in areas both close to (Soares *et al*., 1997) and spatially distant from the production sites, and reduced kelp production might therefore have far-field impacts not predicted by studies in the immediate vicinity of the kelp-beds themselves. The role of beach-cast kelp in supporting a range of macro- and megafauna including shore-birds, especially on sandy shores, has been demonstrated in several studies (Griffiths & Stenton-Dozey, 1981; Bradley & Bradley, 1993; Orr *et al*., 2014).

Although kelp does not normally support high abundances of herbivores, grazing by organisms such as gastropods, can weaken the stipe or lamina increasing the probability of abrasion damage or breakage (Krumhansl *et al*., 2011; Krumhansl & Scheibling, 2011). The presence of encrusting organisms, such as the European bryozoan *Membranipora membranacea*, can also increase hydrodynamic drag on the plants and increase rates of loss (Krumhansl *et al*., 2011; Krumhansl & Scheibling, 2012). These issues are of interest because increased losses of kelp due to abrasion and breakage in particularly stormy periods will reduce the standing stock available for harvesting.

The young stages of several commercially important fish are found in inshore waters and are often caught within, or close to, kelp beds (Smale *et al*., 2013b). Stomach contents of young cod (*Gadus morhua*), pollack (*Pollachius pollachius*) and saithe (*Pollachius virens*), as well as a range of non-commercial species, have been shown to contain kelp-associated fauna (Norderhaug *et al*., 2005). Although kelp-associated invertebrates were important in the diet of saithe, they contained a higher proportion of pelagic copepods compared with the other fish species examined. Norderhaug *et al.* (2005) suggested that they preyed on kelp-associated fauna mainly along the fringes of the kelp beds. Sarno *et al.* (1994) reached a different conclusion observing that schools of young saithe actively foraged in kelp beds in Loch Ewe, whereas pollack remained solitary and used the kelp mainly for cover in order to ambush passing prey.

3.4 Kelps as Complex Habitat Engineers

KEY POINTS

- **Kelp beds support a wide range of associated flora and fauna and are thus important in maintaining biodiversity in inshore waters.**
- **Fallow periods sufficient to allow kelp to recover between harvesting, typically 3-5 years, may be inadequate to allow the associated communities to fully recover.**

In many locations kelp form dense beds which provide permanent or temporary shelter for a wide-range of organisms including fish and invertebrates (Wilkinson 1995, Christie *et al*., 1998a; 2009; Blight & Thompson, 2008).

The stipes of kelps frequently support a range of other plants called epiphytes. Many of these will be red algae, such as *Palmaria palmata, Phyllophora* spp. and *Delesseria sanguinea*, species which can tolerate the reduced light levels generated by the kelp canopy (Whittick, 1983). Filamentous, branched species, such as *Polysiphonia* and *Ceramium* species and coralline encrusting algae, such as *Lithothamnion* spp., are also common epiphytic organisms on kelp.

The holdfasts of larger kelp plants (both *Laminaria* and *Saccorhiza* spp.) also create sheltered habitats and so support a large number of species (hapteron fauna) including gastropods, crustaceans and echinoderms (Edwards, 1980; McKenzie & Moore, 1981). Differences in holdfast structure between kelp species influence the hapteron community composition (Blight & Thompson, 2008).

The lifecycle of most of the epiphytes is annual with die-back occurring in the winter whereas the organisms inhabiting the holdfasts tend to be multi-annual (Norderhaug *et al*., 2002; Christie *et al*., 2009). However, the range of associated species and their abundance tends to increase with the age of the kelp (Rinde *et al*., 1992).

The understorey community also varies with kelp species. For example, the stipes of *L. digitata* are less rigid compared with *L. hyperborea* so that the blades of the former create greater physical abrasion on the substrate and thus have a more impoverished understory community associated. However, certain species like the limpet *Patella ulyssiponensis,* can proliferate in such impoverished communities. Community composition within a monospecific kelp bed also varies with the degree of site exposure (Schultze *et al*., 1990). Dense kelp also cuts light to the understorey so this area tends to be dominated by rhodophycean (red) algae, which are more tolerant of low levels of illumination (Pearse & Hines, 1979; Hagen, 1983).

Kelp beds are used by several species of fish, including some of commercial importance such as cod (*Gadus morhua*), during their early years. The spatially complex habitat that kelp provides probably helps protect these vulnerable stages from predators (Keats *et al*., 1987; Fromentin *et al*., 2001, Juanes, 2007; Smale *et al*. 2013a), as well as providing opportunities for feeding on the associated biota (Seitz *et al*., 2014). Fromentin *et al.* (2001) suggested that patterns in 0-group cod survival might be linked to the amount of macroalgae when examined across different sites along the Norwegian Skagerrak coast, potentially linking kelp removal to the success of recruitment to adult cod populations.

Kelp beds also form important feeding habitats for some seabirds and marine mammals. The growth rate of kelps can be rapid so medium to large-scale harvesting, in countries such as Norway (Vea & Ask, 2011) and France, tends to rely on sequential cropping with a fallow-period (typically 3 to 4 years) to allow the kelp to recover. However, although the kelp itself may regrow within this timeframe, the associated biota may not recover to the original level. There are also concerns that post-harvest recovery will mean that most of the plants are of similar age, again potentially impacting associated biodiversity.

Kelps are thus regarded as habitat forming organisms although in the SEA on kelp harvesting the Scottish Government (2016) noted that '*the nature of inter-specific and regional-scale variability in kelps as habitat formers in the UK (and the wider implications for biodiversity) is poorly understood and remains an important knowledge gap in the field of kelp bed ecology'*.

3.5 Threats to Kelp

KEY POINT

- **There are a number of natural and man-made threats to kelp.**
- **These threats need to be monitored because they can impact the health of kelp beds and can also reduce harvest yields or crop quality, or in the worst cases threaten the sustainability of kelp harvesting.**
- **Kelp may have a coastal protection role so harvesting should avoid orientating harvest strips in the direction of prevailing tides, or removing all kelp around the low water mark.**
- **If harvesting is in areas adjacent to sandy coastlines special attention may be needed to monitoring any impacts on shoreline erosion.**

Healthy kelp beds are stable persistent ecosystems with a high ability to recover after disturbance (Norderhaug & Christie, 2009). This high resilience is largely attributable to the presence of recruit plants in the understorey which can quickly grow to replace adults which die or are lost. However, kelp beds globally are subject to a number of threats including pollution, disease and parasites, over-grazing and climate change (Krumhansl *et al*., 2016).

Kelp can be affected by a range of pollutants which may be present in coastal waters. Hopkin & Kain (1978) demonstrated experimentally that germination of *L. hyperborea* spores (gametophytes) were reduced in the presence of mercury, copper, sodium dodecyl benzoate, zinc and mixed detergent. Considerably higher concentrations of pollutants were required to elicit a decrease in respiration in older tissue. Similar impacts of copper on the release and growth of the early stages of *L. saccharina* were shown by (Chung & Brinkhuis, 1986). However, the water quality around Scotland is generally regarded as high (apart from in a few estuaries such as the Clyde), so pollution may be less of a concern with regard to the health of wild kelp stocks in Scottish waters.

Declines in kelp biomass also have also been reported close to coastal conurbations (Benedetti-Cecchi *et al*., 2001; Connell *et al*., 2008; Foster & Schiel, 2010). The precise causes for the losses often vary from site to site but may include pollution from sewage, increased turbidity or disturbance associated with dredging and shipping or storm damage. Once lost the kelp tend to be replaced with fast-growing turf-forming species, which in turn trap sediment that inhibits recolonization by kelps.

Wild kelps are also affected by a wide range of diseases and parasites (Gachon *et al*., 2010). In North Sea *Laminaria* spp. up to 85% of thalli were infected with microscopic endophytic algae, which in some cases led to distorted stipes and damaged laminae (Ellertsdøttir & Peters, 1997). As a result of problems with artificial cultivation, naturally occurring diseases in kelp have begun to receive increased attention (Egan *et al*., 2014). In relation to wild kelps, seaweed farming can exacerbate such problems through expanding disease reservoirs or the introduction of non-native species or strains (Loureiro *et al*., 2015). Because of the enhanced risks of transmission in aquatic systems, controlling diseases and pests in mariculture is frequently much more challenging than in terrestrial agriculture.

Loss of wild kelp, and its replacement by coralline algae, has been recorded in Japan although the authors were unsure of the original reason for the loss (Noro *et al*., 1983). Such losses are often accompanied by an increase in sea urchins which suppress kelp regrowth (Lang & Mann, 1976; Duggins, 1980). Overgrazing of kelp by sea urchins has been implicated in losses of areas of kelp in California (North & Pearse, 1970), Canada (Lang & Mann, 1976, Mann, 1977, Scheibling *et al*., 1999) and Norway (Hagen, 1983). Destruction of kelp beds by urchins can apparently occur in as little as one year (Hagen, 1983), but again it is somewhat unclear which comes first (Filbee-Dexter & Scheibling, 2014) – are the urchins the cause of the problem or merely a symptom?

In the NE Pacific the role of sea otters as ‘keystone’ species in controlling urchins, and thus in maintaining healthy kelp beds and associated fauna, has been well documented in the California and Aleutian *Macrocystis*-ecosystems and is often cited as a classic example of top-down trophic control (Estes *et al*., 2010). When sea otter numbers were reduced by being hunted for their fur, the kelp beds tended to switch into the alternate urchin-dominated state with knock-on effects to other species (Markel & Shurin, 2015; Estes *et al*., 2016). Mann (1977) suggested that removal of lobsters might have released urchins from predation pressure in St. Margaret’s Bay, Nova Scotia with subsequent loss of kelp. Urchins seem able to persist in areas lacking kelp by adjusting their feeding mode and food sources (Hagen, 1983). In areas where urchins were removed experimentally (Duggins, 1980), or in areas recolonised by sea otters (Breen *et al.,* 1982; Estes & Duggins, 1995), kelp re-established demonstrating that such trophic-reorganisations can, at least in some instances, be reversible (Filbee-Dexter & Scheibling, 2014). In other instances the urchin-barrens appear to become established as an alternate stable-state and thus persist for many years (Filbee-Dexter & Scheibling, 2014). Other means by which urchin populations may naturally be reduced allowing kelp to re-establish are parasites (Hagen, 1987) and disease (Pearse & Hines, 1979; Johnson & Mann, 1988; Scheibling *et al*., 1999).

In Nova Scotia, Scheibling *et al*. (1999) suggested that aggregation of urchins into destructive grazing fronts were the result of migration from deeper water, resulting in a cycle of kelp removal and recovery as the urchins eventually succumbed to disease. This seems to suggest that overgrazing of kelp in this system may be a natural cycle, rather than resulting from anthropogenic pressure. Paradoxically, they also pointed out that a fishery for urchin roe, which developed in the late 1990s, meant that conservation of the urchins became a priority.

Urchin-dominated barrens have also been reported in the NE Atlantic (Filbee-Dexter & Scheibling, 2014; Araújo *et al*., 2016), but in this region there is less evidence that removal of top-predators released pressure on urchins and led to trophic-cascading (Norderhaug & Christie, 2009). In healthy kelp beds the abundance of urchins is generally rather low and their proliferation is controlled by a number of feed-back mechanisms (Hagen, 1983; Norderhaug & Christie, 2009; Filbee-Dexter & Scheibling, 2014). Concerns have therefore been raised that large-scale kelp harvesting could allow urchins to proliferate in recently cut areas (Steneck *et al*., 2004).

In northern Europe there is also a lack of natural predators, such as the sea otter, which specialise on urchins so outbreaks would probably need to be physically or biologically (Miller, 1985) controlled or allowed to progress naturally. It therefore seems important that urchin abundance is monitored in cropped areas using video and/or diver surveys and remedial action considered if a problem appears to be developing (Vea & Ask, 2011).

Climate change is likely ultimately to affect kelps in many locations, although effects in Scottish waters may take a long-time to manifest because the area is roughly in the middle of the latitudinal range of one of the dominant kelp species, *L. hyperborea* (Brodie *et al.*, 2014) and somewhat above the southern limit for *L. digitata* (Assis *et al.*, 2017).

Under a high CO_2 world, *Alaria esculenta* might be replaced with the invasive *Undaria pinnatifida* and such shifts in species can have subtle effects, even when the replacement appears structurally similar. For example, Blight & Thompson (2008) showed that the biodiversity associated with *Laminaria digitata* was higher than for *Laminaria ochroleuca*, which occurs in slightly more warmer waters and has been extending its range northwards in southern England as *L. digitata* retracts.

Small shifts in temperature might affect the balance of species in kelp beds. For example, Werner & Kraan (2004) described how there are increasing amounts of the commercially less valuable *S. polyschides* in *L. digitata* beds in France. Raybaud *et al.* (2013) suggested that the decline in the distribution of *L. digitata* was probably related to increased water temperatures, but cautioned that fragmentation of populations by harvesting could exacerbate the rates of loss. Distributions of the target species in the North Atlantic (Lüning, 1990) suggest that *Laminaria hyperborea* populations can exist at annual average temperatures between 4.2 and 15.6°C, *Laminaria digitata* from -0.6 to 12.8°C, and *Saccharina latissima* from -1.5 to 15.7°C (Burrows, unpublished analysis). Abundance of each of these species is expected to decline as the upper temperature limits currently experienced are approached through ocean warming.

It must be remembered that species losses tend to result from multiple stressors, of which changing temperature is but one (Harley *et al.*, 2012; Brodie *et al.*, 2014). For example, in Western Australia the kelp *Ecklonia radiata* can cope with increased temperatures through metabolic adjustments, but at the cost of decreased resilience to other stressors (Wernberg *et al.*, 2010).

Another example of multiple stressors affecting kelp is in northern California. Since 2013 there appears to have been substantial losses of bull kelp (*Nereocystis luetkeana*) as a result of a series of environmental events, beginning with a large toxic algae bloom followed by increased predation from seastars, ocean warming during the 2014 El Nino and increased grazing by urchins (California Department of Fish and Wildlife, 2016). It has been reported that the kelp forest has been lost across large areas as a result of this sequence of stress events (Freiwald & Neumann, 2017).

As well as impacting the kelp directly, complex community responses to changes in the environment have also been reported. In eastern Tasmania increases in temperatures mean that coastal waters are now above the lower thermal limit for the larval development of the long-spined sea urchin (*Centrostephanus rodgersii*). As well as increased reproduction, heavy fishing of reef-based predators, such as the spiny lobster (*Janus edwardsii*), also seems to have allowed urchin abundance to increase, leading to subsequent overgrazing of the kelp (Ling *et al.*, 2009).

It has also been shown that extreme events, such as heat-waves, can have a disproportionate effect on seaweeds. Such extreme events may be important because studies often model a more gradual warming trend and so may underestimate the impacts (Smale & Wernberg, 2013).

In Scotland, increases in storm intensity and frequency, which are anticipated under climate change scenarios, could have an impact on kelp, although *L. hyperborea* appears to be relatively resilient to storms compared to some other kelp species (Smale & Vance, 2015).

Some authors have suggested that extensive kelp beds have a coastal protection role in reducing wave energy (Andersen *et al*., 1996; Mork, 1996). Removal of large areas of kelp could therefore have impacts on sandy shorelines (Angus, 2017), although this conclusion appears to be based on a limited amount of research. Based on flume experiments, Løvås *et al.* (2001) concluded that the presence of sub-tidal kelp did little to reduce the initial impact of storms on sand-dunes. However, it was also concluded that given successive storms the presence of kelp offshore could reduce the total time that dunes were eroded.

As kelp habitats may have a role in coastal protection, it is recommended that harvesting should avoid orientating harvest strips towards the direction of prevailing tides, or removing all kelp around the low water mark. If harvesting occurs in areas adjacent to sandy coastlines special attention may also be required with regards to monitoring, with additional effort invested into examining any impacts on shoreline erosion.

3.6 Impacts of Harvesting on Kelp

KEY POINT

- **Kelp has the potential to recover from harvesting within a few years but the age structure and habitat complexity of the bed will be reduced.**
- **It is recommended that kelp harvesting in Scotland follows the practice in Norway, with sector-based management. Sectors should be open to harvesting for one year followed by four years' fallow until the next harvesting period.**
- **This frequency should be kept under review as evidence for the effects of any harvest in Scotland emerges. Slower or faster rates of recovery may lengthen or shorten the recommended harvesting cycle.**
- **Considering typical harvesting yields and a five year harvesting cycle, sustainable harvesting would remove 3% of the total biomass from a given area. Therefore the management area should cover an area approximately 33x larger than the area estimated to contain that amount of kelp for a given biomass density.**
- **Annual variability means that in some years a greater number of strips may be required to be harvested to return a target yield. Enlargement of the management area to 50x larger than the area estimated to contain the required amount of kelp for a given biomass density should give enough margin to allow for the possibility of needing to expand the area harvested in low biomass density years.**
- **Adaptive management plans should be developed that reflect locally measured biomass densities and growth rates.**

The choice of harvesting method will obviously affect the overall impacts. In Scotland, kelp harvesting to date has been at a small-scale, using non-mechanical approaches, but in some other countries larger-scale harvesting using mechanical means is pursued. Existing devices include the 'Scoubidou', used in France, to harvest *L. digitata* and kelp dredges used in Norway to harvest *L. hyperborea*.

The 'scoubidou' is a curved hook suspended from a hydraulic arm mounted on the boat. The hook is lowered into the kelp bed and rotated and the blades of the kelp are wound around the rotating scoubidou and pulled onto the boat by the hydraulic crane. Short blades are missed by the device.

In Norway kelp is harvested with a rake-type dredge that is pulled by the boat along the bottom, and which tears the kelp plants from the rock. Harvesting removes all canopy-forming kelp plants in a 4 m wide track, leaving either a barren track or a track with small kelp plants (Lorentsen *et al*., 2010).

These impacts are different to that of hand or mechanical cutting of rockweed (*Ascophylum nodusum*) where the stipe and holdfast are left and can regenerate (Angus, 2017). Kelp recolonization relies on the growth of smaller plants left by the harvesting, or on recruitment of sporophytes from outside of the harvested area (Christie *et al.,* 1998a).

Whilst the impacts of the Norwegian rake-type dredge on the substrate are likely to lower than for other forms of dredging, such as for scallops, some disturbance of the substratum may occur as plant material is dragged to the surface (Scottish Government, 2016).

In the early 1990s, Kelco undertook trial harvesting of *L. hyperborea* and monitored the results. However, the production base at Barcaldine was closed shortly afterwards, and all monitoring data became unavailable. Angus (2017) reported that the results showed that kelp recovery varied between areas, but was generally good at Muasdale and Oronsay, though slower at the former due to sand scour. A third monitoring site was to the east of Colonsay. This remains the only work conducted on the impact of medium- to large-scale harvesting of *L. hyperborea* in Scotland. The Kelco monitoring appears to have concentrated largely on the kelp itself, so that there are no Scottish data on the impacts of kelp harvesting on associated biodiversity. Information on potential impacts has therefore had to be inferred from studies in other countries, notably Norway.

The fact that harvest yields in Norway have been relatively stable over three decades has been cited as evidence that the harvest is sustainable (Vea & Ask, 2011), at least from the point of view of the kelp (Steen *et al.,* 2016).

Werner & Kraan (2004) describe a decline in harvested *L. digitata* beds in France and its replacement *S. polyschides*, a species of less commercial value due to differences in the alginic acid content of the two species. This has meant that, in some years, processors have rejected crops containing over 50% of *S. polyschides* or are paying less than the negotiated price. The increase in the abundance of the less valuable *S. polyschides* may be more related to changes in water temperature rather than harvesting of *L. digitata,* although harvesting might have increased colonisation opportunities for the former species (Raybaud *et al.*, 2013).

Given the high growth rates of *L. hyperborea* under good conditions, recovery of the virgin biomass and frond area may be reached in as little as 3 years after cutting (Kain & Jones, 1976b). However, the same authors reported that it took 4 years for the original stipe lengths to be reached.

Werner & Kraan (2004) reported results from a small experimental strip clearance of *L. hyperborea* in Irish waters. Three months after clearance the area was colonised by small *S. polyschides* and *Dilsea carnosa*. Mobile species such as lobster, crabs and urchins had disappeared. Six months after harvest there was a mixed flora but *Laminaria* spp. only began to appear after one year. Unfortunately, the experiment only lasted one year so that full restoration was not observed.

Steen *et al.* (2016) studied *L. hyperborea* recovery following the commencement of commercial harvesting in Nord-Trøndelag, Norway in 2010. They found that, *L. hyperborea* had regained its dominance after 4 years' post-harvest, with the kelp biomass appeared restored, but that the age and height of individual plants and epiphyte communities were still below pre-harvesting levels. The re-growing kelp plants had a higher growth rate compared with plants in pristine kelp beds, a result might be expected from the opening of the canopy allowing more light to reach the plants. After four years' recovery the canopy density was higher than in pristine beds, although canopy height was lower. The authors noted that the age structure of plants collected four years after harvesting indicated that recruits which were already present as understory vegetation prior to harvesting, must have contributed substantially to the restocking. However, the density of small understory kelps four years post-harvesting was lower than it had been. The authors suggested that this might lead to slower recovery if future harvests occurred before the stocks of understory recruits were restored.

A commonly reported effect of mechanical harvesting is a reduction in the age-range of the plants in recovering areas. In general the age range of plants will tend to be reduced to the inter-crop interval (Werner & Kraan, 2004).

As well as altering the age and size composition of the kelp itself, harvesting will have impacts on associated communities. Christie *et al*. (1998a) compared kelp, epiphytes, and holdfast (hapteron) fauna at un-harvested and harvested sites along the Norwegian coast. It was found that a new generation of canopy-forming kelp developed within 2–3 y post-harvest and that the percent cover, abundance and number of epiphytic species increased over time. However, the authors noted that epiphytic communities were not totally re-established in the fallow period of 4 years. There were also some regional differences with recovery of the kelp bed being slower in the northernmost region.

Smale *et al*. (2013a) stated that kelp-associated communities can take 7-10 years to recover fully, referring to Christie *et al*. (1998b). However, the Christie *et al*. actually reported that the virgin kelp bed they studied consisted of plants mainly 7-10 years old – there was no mention of full recovery of associated communities taking this amount of time. However, in the discussion it was stated that '*As the kelp plants form a habitat of limited duration (maximum 10 y found at Rogaland and 14 y at Smøla), the flora and fauna of this community must be adapted to a regular colonization of new kelp plants. Thus, a kelp bed community may be recovered during a period of approximately one kelp generation*.' Following this argument, the time taken for full community recovery should thus be similar to the age distribution of plants in un-harvested kelp beds, but the age range of plants will vary somewhat with location. The degree to which such regional variation in kelp growth would affect the recovery times of the associated communities does not appear to have been studied.

Wave exposure is another important factor influencing the organisms associated with kelp (Steen *et al.,* 2016). Variations in wave exposure between harvested and control sites may therefore confound effects of kelp harvesting on the recovery of associated flora and fauna.

For Scotland, the Government's SEA report (Scottish Government, 2016) mentions that future harvesting of *L. hyperborea* might use a comb-like rake similar to that used in Norway, but harvesting in strips, rather than 'clear felling'. This does however have implications for the total area which might be impacted and for economic viability as it would tend to increase the overall distances between the un-loading port and the resource (see Section 6).

3.6.1 Kelp plant recovery times and recommendations for sustainable harvesting

Most of these studies on post-harvest recovery of kelp population density and plant size structure have been commissioned from Norwegian kelp researchers to guide sustainable kelp harvesting practices in the Norway. The practices permitted in Norway reflect recommendations developed from this evidence, modified as further issues and considerations are raised. The most recent paper by Steen *et al.* (2016) stated *"[the coastline] is divided into latitudinal sectors typically one nautical mile (or latitude minute) wide. Each sector is open for kelp harvesting for 1 year, followed by a 4-year fallow period in a cyclic rotation."* There is no evidence to suggest that this is not good practice in relation to recovery of kelp plants, given the harvesting methods used in that country. Given that cost-effective harvesting will not be 100% efficient in removing plants from a sector, this practice will leave sufficient intact reproducing adult plants to allow recolonization from within each sector.

It is therefore recommended that kelp harvesting in Scotland follows the practice in Norway, with sector-based management in which sectors are open for one year followed by four years' fallow until the next harvesting period. The four year fallow period will allow for both recolonization of new plants and the growth of subadult plants to replenish the harvestable stock. This frequency should be kept under review as evidence for the effects of any harvest in Scotland emerges. Slower or faster rates of recovery may lengthen or shorten the recommended harvesting cycle.

For developers looking to harvest kelp, a sensible approach would be to define the target volume of kelp biomass that is desired to be collected (e.g. 1,000 t), and to use the kelp locational maps provided within this report to estimate the boundaries of the area where this harvestable quantity may be located. Once this is established, the size of management area that would be needed to sustainably harvest the kelp can be calculated as set out below.

Typical kelp extraction removes 15-20% of biomass from each one-nautical-mile-wide sector in one harvesting year. Sectors are recommended to be left fallow for four further years (Werner & Kraan, 2004). This means that over a five year cycle, sustainable harvesting practice would remove 15-20% of the 20% of area available (i.e. not fallow) each year, leading to 3-4% of total biomass annually removed across the entire area managed for kelp extraction. Therefore, if a harvester has selected a location based on estimates that it contains a required target yield (e.g. 1,000 t), then **the boundaries of the kelp management area should be extended to cover an area approximately 33x larger than the area estimated to contain the target yield.** For example, a 1,000 t annual yield from an area with an average of 5 kg/m^2 kelp would cover 0.2 km^2 if 100% kelp extraction occurred. The total area required to sustainably harvest that harvest would therefore be:

33 x 0.2 km^2 = 6.7 km^2 (assuming all the kelp is at a density of 5 kg/m^2)

Where lower average biomass density values are encountered, a greater spatial area will need to be covered by the management area.

The potential for yearly variability in kelp biomass density (Section 2.3) means that in low biomass years, at perhaps 30% of the long-term average as in the Walker (1956a) study, a greater number of strips may be required to be harvested to return a target yield. **Enlargement of the management area to 50x larger than the area estimated to contain the required amount of kelp (for a given biomass density) should give enough margin to remove the need to expand the area harvested in low biomass density years.**

Adaptive management plans should be developed that reflect locally measured biomass densities and growth rates (using techniques and frequencies of surveys outlined in Section 3.9). Before such surveys can be made, the recommendations above should allow the design of a sustainable harvesting plan.

3.7 Impacts of Harvesting on Kelp Associated Communities

KEY POINT

- **Kelp play important roles in supporting other flora and fauna and commercial-scale kelp harvesting is known to lead to local-scale impacts on these associated biota.**
- **In order to facilitate recovery of harvested areas, harvest plans should be designed so that stands of un-cropped kelp are left between cut areas to reduce the impacts on kelp associated biota.**

As emphasised in Section 3.4, kelp are ‘ecosystem-engineers’ and so are important for the associated communities of organisms. When considering the impacts of harvesting kelp it is not sufficient to consider only the impacts on the kelp itself. For example, Christie *et al.* (1998a) noted that a complete restoration of the kelp communities and their ecological functionality would require a kelp harvesting cycle of more than five years.

As harvesting tends to reduce the age range of the plants, it will tend to reduce abundance and biodiversity of the associated communities (Rinde *et al.*, 1992). However, many of these associated organisms appear to have reasonably high mobility so that providing there is a near-by source, re-colonisation may be quite rapid (Norderhaug *et al.*, 2002).

Whittick (1983) and Steen *et al.* (2016) noted that epiphytic assemblages on kelp stipes are often dominated by red algae. When kelp is cleared these epiphyte communities are rapidly lost and replaced with faster growing algae tolerant of higher illumination levels (Hawkins et al. 2009). Gradually epiphytes begin to reappear but as the re-developing kelp plants normally have faster growth, the kelp begins to restrict light penetration to an even greater extent than in a mature kelp bed, and thus slows the growth and re-establishment of the epiphytic flora. It has been stated that a more impoverished epiphyte community could have negative ecosystem impacts because epiphytes increase habitat complexity (Christie *et al.*, 2007), play a role in trophic transfer and act as refuges for a variety of fauna (Norderhaug *et al.*, 2002).

Christie *et al.* (2003) showed that the abundance of species associated with *L. hyperborea* was strongly related to the habitat volume (i.e. to the size of the plants). Since growth rates of kelp do vary with location, there will be site-based variations in the abundance of associated species.

In relation to the functional role of kelp in Scottish waters, the 2016 SEA report (Scottish Government, 2016) noted that kelp beds are utilised by juvenile fish of commercial importance, such as cod. However, most of the experimental and observational studies on habitat preference in young cod have focussed on seagrasses, rather than kelp (Juanes 2007). The study by Keats *et al.* (1987), based in eastern Newfoundland, looked at associations of juvenile cod with a non-laminariad seaweed, *Desmarestia aculeata*. The study by Fromentin *et al.* (2001) does implicate the abundance of *L. hyperborea* in relation to juvenile cod survival, but is almost entirely based on statistical modelling of the variability in cod recruitment time-series. The link with macroalgae is inferred in that study based on geographical differences in the results. Although it is clear that a range of juvenile fish, including cod, are found in kelp beds it is difficult to evaluate what the relative importance of different complex habitats is at the stock level. For example, Elliott *et al.* (2016) found densities of juvenile cod to be higher on mixed gravel and maerl compared with boulder-cobble with high macroalgal (kelp) cover, or sand with <25% algae or seagrass cover. They did caution however that the other habitats might be important at night as cod are known to exhibit diel-movements.

Steen *et al*. (2013) used cameras and fish and crab traps to record the abundance of fish in harvested areas of *L. hyperborea* and compared the results with un-harvested areas. They concluded there were no significant differences in observed abundances before and after harvesting. The results were against a stronger difference between years in both harvested and un-harvested areas.

Some additional studies to those cited in Scottish Government (2016) support the contention that medium- to large-scale harvesting of kelp will affect the abundance of associated fish. Lorentsen *et al*. (2010) studied changes associated with commercial *L. hyperborea* harvesting in the Sula Archipelago, Central Norway. Harvesting follows a ‘belt’ design on a 5-year harvest and recovery cycle but the study was only able to assess impacts up to 1 year post-harvest. They found that the abundance of small gadoids was associated with un-harvested, high kelp cover versus harvested or low-kelp cover areas, the abundance being lower in the latter areas. However, there was no significant effect of kelp cover on larger gadoids. There was a similar association of cormorant (*Phalacrocorax carbo*) numbers with un-harvested areas and the birds also made fewer dives per foraging trip in these zones, whilst recently harvested areas were avoided completely by the birds. The authors concluded that displacement of small fish affected the cormorant behaviour but were careful to point-out that the fate of the juvenile fish displaced by the kelp harvesting was unknown.

Whether harvesting of kelp would have noticeable impacts on gadoid stocks is difficult to determine especially considering our relatively poor understanding of the fine-scale distribution of juvenile gadoids in inshore habitats (Magill & Sayer, 2004). The issue of impacts of large-scale kelp harvesting on commercial stocks however remains a major concern raised in countries such as Norway. It will undoubtedly also be a key issue in Scotland when considering the potential for large-scale kelp harvesting, especially given that the poor stock status of several important commercial gadoid species off the Scottish west coast, including cod and whiting (*Merlangius merlangus*) (ICES, 2016; 2017).

Burrows *et al*. (2014d) concluded that ‘*while it is recognised that a conservative ecosystem-based management approach is a pre-requisite for achieving sustainable production, the baseline knowledge on the structure and functioning of kelp ecosystems at regional scales needed to underpin such an approach is currently lacking’*.

3.7.1 Community recovery and recommended sustainable harvesting practice

These studies show the importance of maintaining intact kelp forests, or those in an advanced state of recovery, in close proximity to recovering kelp areas to improve the rates of recolonization of young kelp plants by the associated fauna and flora. The Norwegian practice is to ensure that such that no field harvested is bordered by one that has been harvested in previous years (Werner & Kraan, 2004). **It is recommended that kelp harvesting practice in Scotland follows the Norwegian model of harvesting in strips one nautical mile wide, such that no strip borders one that has been previously harvested. If sufficient kelp habitat is available, each harvested strip should be bounded by permanently fallow (unharvested) strips to ensure proximity to intact forests.**

3.8 Environmental Impact

Proximity of records to areas predicted as suitable for kelp (Figure 13) show which Priority Marine Features (PMFs) may be affected by a harvesting industry. Here, records from the SNH GeMS database (Geodatabase for Marine Habitats and Species adjacent to Scotland, accessed 2016) of presence of habitats and species designated as PMFs have been spatially referenced to a data layer comprised of the total amount of predicted kelp habitat (P(Rare)>0.5) within 2 km of a grid cell.

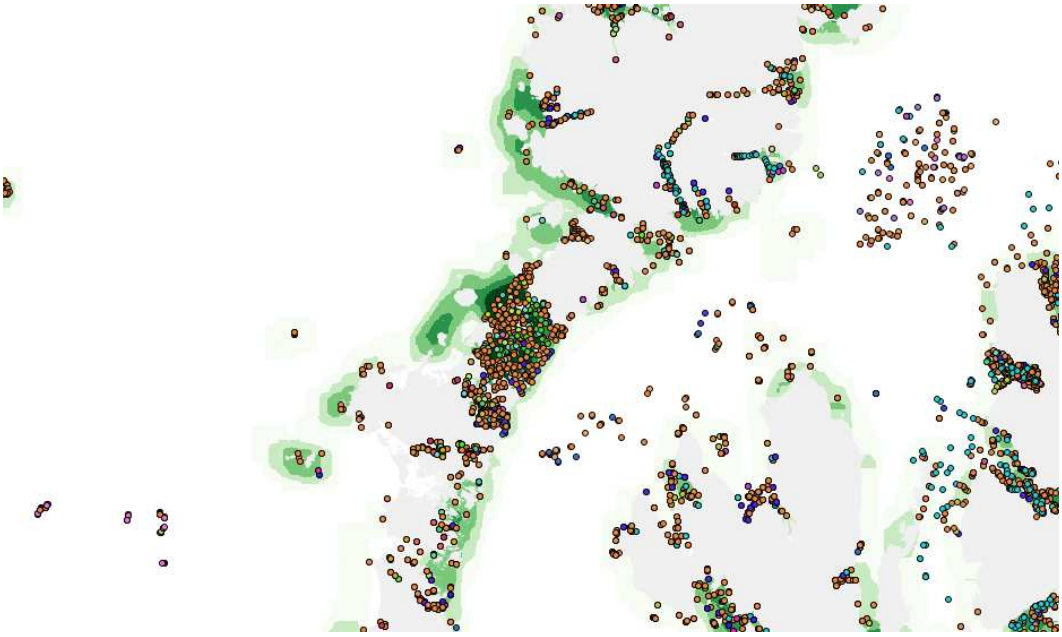


Figure 13. *Priority Marine Features in proximity to areas of predicted suitable kelp habitat. Occurrence of PMFs has been tabulated by the total area of predicted kelp within 2km (5km shaded areas above; Table 7).*

For PMF habitats (Table 7 left), unsurprisingly, SNH records of kelp habitats (shaded in the table) tended to be mostly seen (>85% observations) within 2 km of predicted suitable kelp habitat. Many of the coastal reef-building and habitat-creating species also co-occurred with suitable kelp habitat: serpulid aggregations, flame shell beds, native oysters and horse mussel beds. Less obviously, sediment habitats such as burrowed mud, tide-swept sands and maerl were also in close proximity to predicted suitable kelp habitat. These associations should be treated with caution, since most of the coastline is predicted to have at least some kelp, and as a consequence most coastal records will be somewhere near predicted suitable kelp habitat. That said, the results of this analysis do show the close proximity of predicted suitable kelp habitat for the listed PMFs, and the potential for impacts on these species and habitats.

Notable associations of PMF species with suitable kelp habitat can be seen in Table 7 (right), with 6 species having more than 80% of records within 2 km of some suitable kelp habitat. Grey seals and harbour/common seals are highly likely to be associated with kelp, likely to be a consequence of seal haul-outs being located in rocky areas. Other coastal species that emerged as concentrated around suitable kelp habitats included native oysters (*Ostrea edulis*), ocean quahog (*Artica islandica*), common skate, eels, otters (top half of Table 7). Species not associated with suitable kelp habitats were those usually considered to be open-water or pelagic species (mackerel, herring, whiting, sandeels, anglerfish).

Species with <5% records within 2km of predicted suitable kelp habitat included: Atlantic herring, Spiny dogfish, Atlantic halibut, Blue whiting, European river lamprey, Horse mackerel, Norway pout, White-beaked dolphin.

Table 7. *Occurrence of habitats (left) and species (right) designated as Priority Marine Features within 2km of predicted kelp habitat in Scotland*

PMF Habitat	Total	% <2km		PMF Species	Total	% <2km
Serpulid aggregations	222	100%		Native oysters	115	93%
Flame shell beds	291	100%		Sand goby	763	92%
Sea loch egg wrack beds	138	98%		Pink sea fingers	12	92%
Tide-swept coarse sands with burrowing bivalves	104	96%		Harbour / common seal	984	86%
Maerl or coarse shell gravel with burrowing sea cucumbers	149	96%		Grey seal	1,161	84%
Kelp and seaweed communities on sublittoral sediment	2,144	94%		Otter	870	80%
Native oysters	21	90%		Sea trout	22	77%
Kelp beds	2,962	89%		Eel	58	74%
Tide-swept algal communities	496	87%		European spiny lobster	131	73%
Tide-swept algal communities and Kelp beds	144	85%		Northern sea fan and sponge communities	370	69%
Maerl beds	1,446	85%		Low or variable salinity habitats	78	65%
Burrowed mud or Inshore deep mud with burrowing heart urchins	624	85%		Northern feather star	458	64%
Low or variable salinity habitats	663	84%		Saithe	757	64%
Horse mussel beds	473	82%		Burrowed mud	1,281	63%
Burrowed mud	2,257	80%		Burrowing sea anemone	15	60%
Blue mussel beds & Low or variable salinity habitats	31	77%		Fan mussel	150	59%
Inshore deep mud with burrowing heart urchins	44	77%		Ling	443	55%
Seagrass beds	963	52%		Ocean quahog	577	54%
Offshore deep sea muds	2	50%		White cluster anemone	182	54%
Northern sea fan and sponge communities	550	45%		Atlantic salmon	10	50%
Blue mussel beds	407	32%		Basking shark	6,408	44%
Intertidal mudflats	763	13%		Cod	933	33%
Offshore subtidal sands and gravels	304	9%		Common skate	451	31%
Cold-water coral reefs	6	0%		Anglerfish	409	19%
				Sandeels	1,511	15%
				Minke whale	22	9%
				Atlantic mackerel	389	7%
				Harbour porpoise	225	6%
				Whiting	804	6%

3.9 Techniques for Assessing Yields and Monitoring the Impacts of Harvesting and Recovery

KEY POINT

- **Costs for establishing environmental baselines and for monitoring the impacts of harvesting must be factored in to development plans.**
- **Such costs may be initially high but would be expected to reduce over time.**

Angus (2017) concluded that the abundant seaweed resources of Scotland could make a valuable contribution to economic development but, given the environmental sensitivities, any medium- to large-scale harvesting would need a phased development informed by robust monitoring. The costs of surveying and monitoring thus need to be factored in to any plans for developing mechanised kelp harvesting in Scotland.

Given the scale of potential impacts, any large-scale harvesting plans would probably require an Environmental Assessment. The term ‘Environmental Assessment’ (EA) is used here to distinguish from cases where an Environmental Impact Assessment (EIA) is formally required; the differences between EA and EIA are addressed in Section 5.2.2 of this report.

Due to a paucity of data from Scottish waters relating to the potential impact of harvesting and subsequent recovery of kelp habitats, it is not possible to suggest ‘threshold’ figures where a level of harvesting can be deemed to have an insignificant impact on kelp habitats, and thus be exempt for undertaking an EA. As the industry develops and more data is acquired from monitoring programmes, it may be possible to identify a harvesting threshold which dictates whether an EA is required.

Regardless of the requirement for EA or EIA by the regulator, some initial surveys of the distribution, composition and biochemical composition of the kelp resource are likely to be required pre-harvest for commercial reasons, as harvesters will need to gain an understanding of the distribution of the kelp resource over the intended area of extraction. The scale (and therefore cost) of these initial surveys will be dictated by the size of the area and the amount of kelp intended to be harvested.

An EA/EIA would however go further and require collection of a wider range of data and information to inform an evaluation of the possible impacts of harvesting at specific sites, to ensure that there are no impacts on protected species (either within the site or associated with the site), to document recovery post-harvest to inform harvest plans, and to consider mitigation options and alternatives where impacts are identified.

An EA/EIA should also incorporate a strong element of stakeholder engagement throughout. Although sometimes seen as an un-necessary burden by industry, E(I)A if done well can smooth project development and save costs in the long-term by forestalling stakeholder concerns (Glasson *et al*., 2012).

For an EA/EIA it must be recognised that initial survey effort (establishing baseline conditions) and monitoring impacts over several harvest and recovery cycles are likely to be higher than the eventual costs of long-term monitoring, although this assumes that the locations harvested are not shifting over the longer-term. This is a typical pattern in the development of any industry in a new habitat but can be problematic, especially when regulators are unsure about potential impacts and what needs to be monitored (Fox *et al*., 2017). To avoid this problem the Environmental Monitoring Program needs to be developed through iterative discussions between the proposer, regulators and other stakeholders (Glasson *et al.,* 2012). However, as more is learnt about the impacts of the project, some of the monitoring can usually be scaled-back over time.

Monitoring data from both harvested and reference sites are also a valuable scientific resource. There is a general lack of long-term time-series on changes in biomass, species composition, size and age structure and trends in associated flora and fauna for European kelp beds (Araújo *et al.,* 2016). If harvesters can be persuaded to make such data publically available, either voluntarily or as a licence condition, it would provide a valuable scientific service contributing to longer-term society benefits as well as contributing to sustainable harvest management (Fox *et al*., 2017). Accessibility to such data would allow for gaps in knowledge concerning the potential impacts that kelp harvesting may have on the environment.

A range of techniques have been used in previous studies and it is likely that some of these will need to be deployed both in assessing the initial resource, in developing any EA which may be required, and in monitoring the impacts of harvesting (Table 8). The Table includes the state indicator addressed by each modelling technique, the rationale behind measuring each indicator and a suggested suitable frequency for the use of each method. Indicative costs are given for some of the methods, as well as examples of studies that use these approaches. Finally, the importance of each technique is given by a relative priority assessment. As examples, it is considered vital (priority 3) that a modelling assessment (provided at a large scale by Section 2 of this report) of the likely resource extent and biomass be attempted in the pre-harvest phase of the development. Estimation of the distribution of plant sizes in kelp populations is a much lower priority (priority 1), since the relevant information on biomass and plant density is more easily obtained through other means.

Table 8. *Techniques which may be used in monitoring the impacts of kelp harvesting*

Receptor	**State indicator**	**Rationale [Frequency]**	**Technique – use in monitoring**	**Comments**	**Cost**	**Examples**	**Priority (1-3 low-high)**
Kelp	Habitat suitability	To estimate suitable habitat and biomass of kelp species. **[Pre-harvest.** **In climate scenarios]**	Potential habitat can be assessed based on models	Gives statistical likelihood of kelp being present at broad spatial scales depending on grain of the underlying data, results have to be ground truthed	-	This report Section 2	3
Kelp	Abundance, plant density	**Recovery** of harvested areas. **[Pre-harvest.** **Annually in exploited areas.** **Five-yearly across broader areas.]**	Grab or dredge samples	Quite widely used method, results rather sensitive to the design of the grab, statistically well designed surveys required to capture spatial variability. Surveys need to be conducted across seasons and years to capture temporal variability.	Grab survey ca. £2-4k per day	Wilkinson (1995); Husa (2014)	2 (pre-) 1 (Annual) 1 (5 yrs)
Kelp	Abundance, plant density	As above	Distribution can be assessed using acoustics	Can establish extent and canopy height but ground truthing required to confirm biomass estimates	Ca. £3-5k per day to cover 2 km^2 (NB. Based on 100m line spacing)	This report Section 2.7.1	3 (pre-) 2 (Annual) 1 (5 yrs)

Receptor	State indicator	Rationale [Frequency]	Technique – use in monitoring	Comments	Cost	Examples	Priority (1-3 low-high)
Kelp	Plant size distribution	**Resource** estimation **Recovery** **[Pre-harvest. Annually in examples of exploited areas.]**	Regrowth can be assessed using towed cameras	Relatively rapid technique capable of covering large areas relatively quickly, will give an indication of kelp regrowth, and contribute to adaptive management	Ca. £3-5k per day to cover 2 km2 area (NB. Based on 100m line spacing)	Steen *et al.* (2016)	3 (pre-) 3 (Annual)
Kelp	Plant growth	**Recovery**, showing the rate of return of plants to harvestable size **[5-yearly in examples of exploited areas.]**	Tagged plants and by punching small holes in the lamina and following growth over a season – results can inform models of kelp productivity	Relatively established low tech. method but many plants may need monitoring to capture variability across a bed, will require use of divers increasing cost		Sjøtun *et al.* (1993)	1

Receptor	State indicator	Rationale [Frequency]	Technique – use in monitoring	Comments	Cost	Examples	Priority (1-3 low-high)
Kelp	Age distribution	**Resource dynamics**, showing dominance by age cohorts and survival rates **[Pre-harvest.** **Annually in examples of exploited and unexploited areas.]**	Age distribution of plants can be analysed based on rings laid down in the stipes	*L. hyperborea*, grazing of stipes by *Patina pellucida* can make age determination difficult. An indication of the time which the associated communities might take to recover fully is given by the maximum age of the plants in an un-harvested bed.		Kain & Jones (1963b)	3 (pre-) 2 (Annual)
Epiphytes on stipe	Abundance and species richness in kelp habitat biota	**Community recovery** **[5-yearly in examples of exploited areas.]**	Identification either *in situ* using divers or on samples returned to the laboratory	Requires laboratory-based taxonomic expertise or training of diver surveyors.	Ca. £2k per day for dive team	Christie *et al.* (1998a)	3 (5 yrs)
Hapteron fauna	Abundance and species richness in kelp habitat biota	**Community recovery** **[5-yearly in exploited areas.]**	Collection and return of plant holdfasts to the laboratory for examination	Requires careful *in situ* collection to avoid loss of organisms from the holdfast, requires taxonomic expertise in the laboratory.			2 (5 yrs)

Receptor	**State indicator**	**Rationale [Frequency]**	**Technique – use in monitoring**	**Comments**	**Cost**	**Examples**	**Priority (1-3 low-high)**
Associated benthic flora and fauna	Abundance and species richness	**[5-yearly in exploited areas.]**	Various grabs, small sleds or cameras have all been used	Accurate data on smaller benthic epifauna and on infauna requires samples to be returned to the laboratory for detailed analysis, requires taxonomic expertise in the laboratory	Grab survey ca. £2-4k per day. Sample infaunal analysis – benthic grab ca. £250 per sample		2
Associated flora and fauna – fish	Abundance and species richness of fish associated with kelp	**[5-yearly in exploited areas.]**	Towed cameras, baited cameras, fish traps	Changes in abundance in harvested are compared with un-harvested locations. Because fish count data are highly variable, obtaining sufficient replication for reasonable statistical power is challenging. Multiple surveys will be required across seasons and years to capture temporal variability. Diurnal variability is an issue for migratory species moving in and out of kelp beds.	Ca. £3-5k per day to cover 2 km2 area (NB. Based on 100m line spacing)	Steen *et al.* (2016)	3

Receptor	State indicator	Rationale [Frequency]	Technique – use in monitoring	Comments	Cost	Examples	Priority (1-3 low-high)
Associated flora and fauna – fish stocks	Contribution of kelp habitats as nursery areas for fishes	**Identification of sensitive areas** **[Once – as a research project]**	Population modelling	Determining if harvesting kelp might impact offshore stocks would be challenging. Population modelling might be a useful avenue to explore. Despite much emphasis in recent years on nursery grounds as "essential fish habitat", we are not aware of any studies where population modelling has been used to assess the effect of localised impacts on nursery or juvenile habitats on adult stocks in the marine environment.	Difficult to cost as would really be a research project	For a fresh water example see Hayes *et al.* (1996)	1 (given the research element)
Associated flora and fauna - seabirds	Contribution of kelp habitats as feeding areas for seabirds	**Identification of sensitive areas** **[Pre-harvest.]**	Observer recording	Often used to collect baseline data on seabird use of a site but will be affected by weather and sea-state conditions. Visual surveys are also difficult to conduct at night. Surveys need repeating across tidal cycles, seasons and years to capture full range of temporal variability.	Ca. £200-300 per day for trained bird observer		2 (desirable but not essential)

Receptor	**State indicator**	**Rationale [Frequency]**	**Technique – use in monitoring**	**Comments**	**Cost**	**Examples**	**Priority (1-3 low-high)**
Associated flora and fauna - seabirds	Contribution of kelp habitats as feeding areas for seabirds	**Identification of sensitive areas** **[Once – as a research project]**	Tagging	Recording tags have been used to look at changes in diving behaviour of birds comparing harvested and un-harvested areas of kelp. Technique can also provide information on extent to which breeding birds forage within a site. Data may be biased towards adult birds which are generally tagged on land at their breeding colonies.	Tagging based studies tend to be expensive and are normally only conducted as part of a research project	Lorentsen *et al.* (2010); Fox *et al.* (2017)	1 (given the research element)
Associated flora and fauna – mammals - seals	Contribution of kelp habitats as feeding areas for seals	**[Pre-harvest.** **5-yearly in exploited areas.]**	Observer recording	Existing data on seal distributions may permit the initial pre-harvest assessment	Ca. £200-300 per day for trained marine mammal observer		3 (pre-harvest) 2 (5 yearly)

The costs associated with each technique vary widely and are affected by multiple factors, such as the survey vessel and staff time required, the logistics of accessing the survey site, the amount of spatial and temporal replication required.

It must be noted that Table 8 presents a range of possible survey techniques for both baseline assessments of features and monitoring purposes. The amount of monitoring required at a given site will have to be determined on a case by case basis, as the assessments of some features may be of utmost importance in some areas, or negligible and unnecessary in others.

A minimum baseline dataset which is likely to be required by licencing authorities would be mapping of kelp biomass and age distributions, some data on use of the kelp bed by other biota and an evaluation of whether the kelp bed is important for seabirds and marine mammals. The level of survey data required (if any) for the latter two receptors would be affected by how close the kelp bed was to known seabird and marine mammal sites.

It is also pointless collecting field data unless they are converted into scientifically credible products. Any survey or monitoring program thus needs to be undertaken by staff with an appropriate level of data analysis, statistical and interpretative skills to ensure that robust and defendable conclusions are reached.

This latter point is particularly important in relation to developments which may prove controversial as the evidence collected and presented in support of “sustainability” of the activity will undoubtedly come under critical examination.

3.9.1 Recommendations for monitoring kelp resources and associated communities

The techniques outlined in Table 8 all provide useful information relevant to both the harvesting industry and any regulating bodies. Ultimately, the level of monitoring required at a particular area will have to be determined on a case by case basis. This will ensure that all features pertinent to the area are considered, and where appropriate, decisions made to not conduct monitoring (i.e. no marine mammal monitoring in an area where no mammals are known to occur). As a minimum it is recommended that, for those areas selected as suitable for harvesting:

- **A pre-harvest assessment across the entire proposed area is made of: (i) potential kelp habitats indicated by models; (ii) actual kelp habitats and biomass densities using acoustic methods and towed cameras, supplemented by grab samples.**
- **Annually, smaller representative areas (n=3) of unharvested/recovered beds and 1 to 4 years’ post-harvest beds should be assessed to track rates of recovery of kelp in the area, minimally by acoustic, video and grab methods**
- **Every five years, kelp habitats and biomass densities should be re-evaluated across the entire area using acoustic methods and towed cameras, supplemented by grab samples. Recovery of kelp-associated ecological communities including epiphytes and fishes should be assessed in selected harvested areas and compared to nearby unharvested kelp habitats, using video and diving methods.**

- **Independent evaluation of the monitoring data should happen annually, with more in-depth review every five years.**

Information gathered by monitoring should be used to inform adaptive management and to address stakeholder issues. Where site-specific issues arise, the monitoring plan should be modified or supplemented as appropriate to inform on any potential impacts.

3.10 Potential Impacts of Kelp Harvesting on other Industries

Large-scale kelp harvesting could impact some other fishing sectors. Mobile gear fishers will tend to avoid kelp beds and will therefore unlikely to be affected. However, static gear inshore potters targeting crab and lobsters could be the sector most likely to be impacted, since harvesting activities may directly damage their gear.

Detailed data on the locations of inshore fishing in Scotland are not available. This is because smaller fishing vessels are not required to carry automatic vessel monitoring systems (VMS). There are on-going trials with developing fishing activity monitoring systems suitable for deployment on smaller inshore vessels (Scottish Inshore Fisheries Integrated Data System (SIFIDS) Project), but these systems have not been rolled out across Scotland.

The best current source of locations of inshore fishing activity (< 15 m sector) for Scotland comes from Marine Scotland's ScotMap project. Data were collected during face-to-face interviews with individual vessel owners and operators on their fishing activity for the period 2007 to 2011. The dataset was based on interviews of 1,090 fishermen. Not all fishermen initially targeted for the ScotMap project were interviewed (72% vessel coverage overall). Individuals defined their fishing areas with variable levels of precision and response rates also varied with location.

Because fishing activity will be strongly related to seabed bottom type (e.g. *Nephrops* creeling on muddy ground, crab and lobster potting on rocky ground), it is likely that the broad spatial patterns of activity will not have changed. However, fishing activity at finer spatial-scales may well have changed over time as a consequence of fishers leaving or entering the industry, or of other developments affecting access to the grounds such as the installation of fish-farms.

The overall patterns of inshore fishing activity do suggest large amounts of overlap between areas where inshore fishing occurs and the areas of habitat where kelp might be found (Figure 14). However, this overall pattern must be partitioned by fishing type.

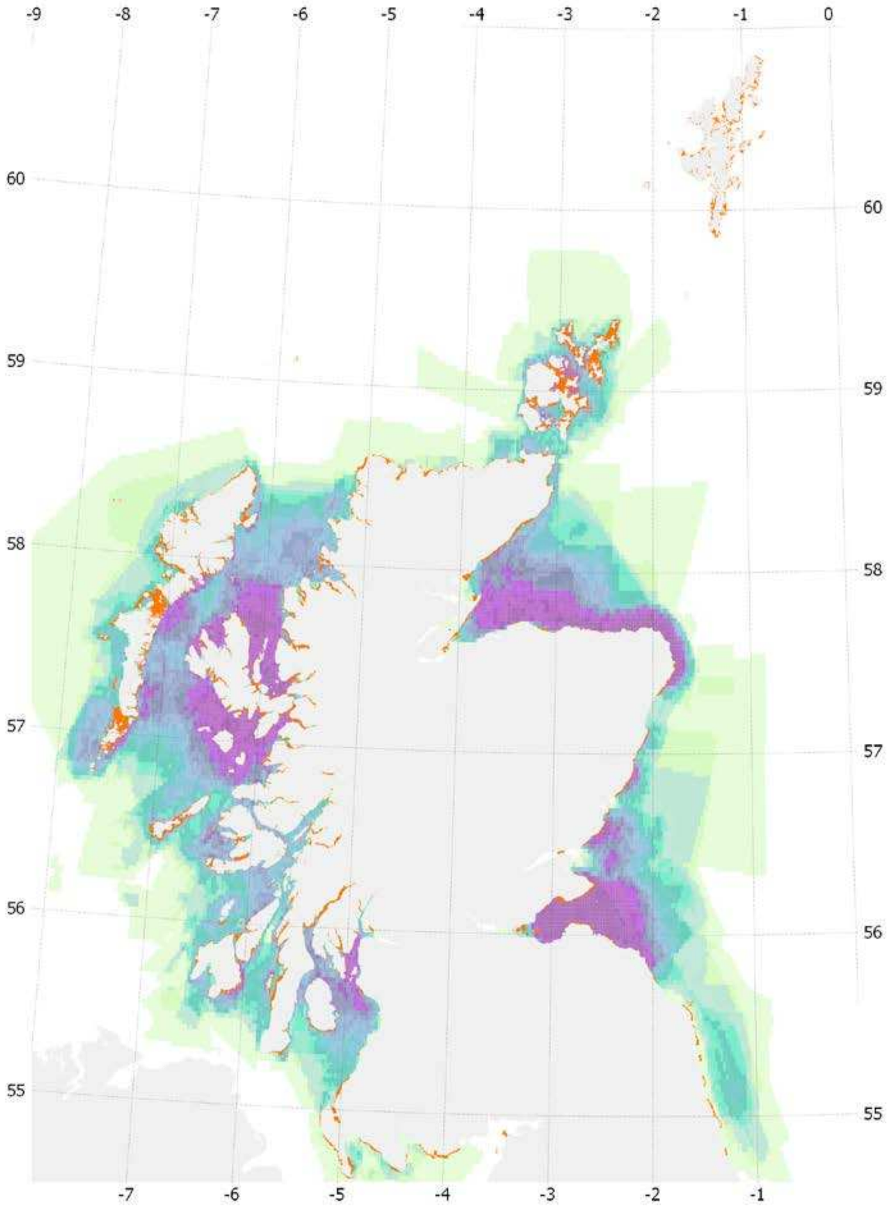


Figure 14. *Total number of inshore fishing vessels (green 0-5, blue 5-25, purple >25) operating from the Marine Scotland ScotMap project. Kelp habitat is shown as orange shading.*

The deployment of pots and creels to catch crabs (both velvet and brown) and lobsters takes place all around the Scottish coast (Figure 15). The main areas for this activity are around Shetland (not included in ScotMap), Orkney and the western coast. There are likely to be spatial overlaps between potting areas and kelp, although this would need investigating at finer spatial scales than the ScotMap data allows to understand if kelp harvesting would conflict with this activity.

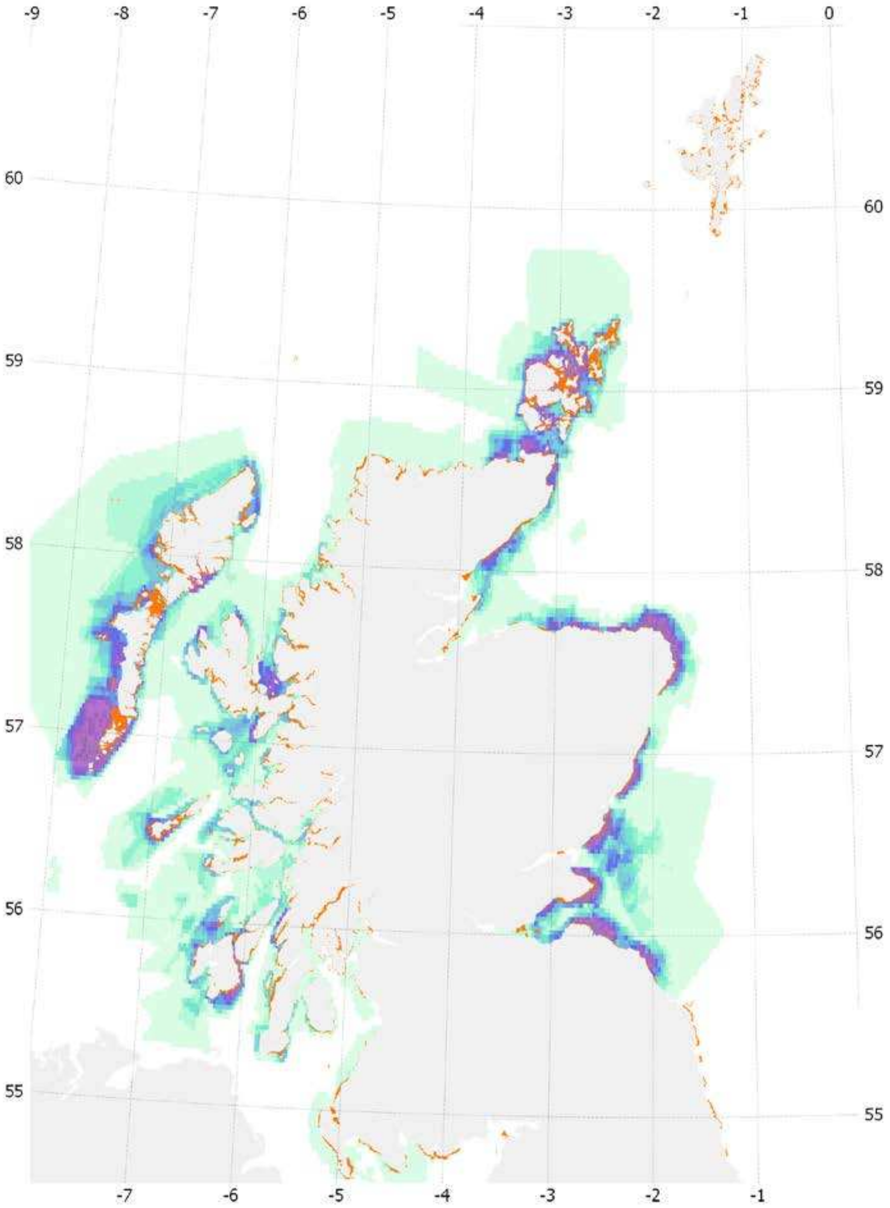


Figure 15. *Inshore fishing locations: crab and lobster pots (green 1-3, blue 4-12, purple >13) from the Marine Scotland ScotMap project.*

Trawling for *Nephrops* takes place right around the Scottish coast (Figure 16). Again this activity is unlikely to be directly impacted by kelp harvesting because *Nephrops* live in muddy habitats which are unsuitable for kelp. This fishery is not likely to be directly impacted by kelp harvesting.

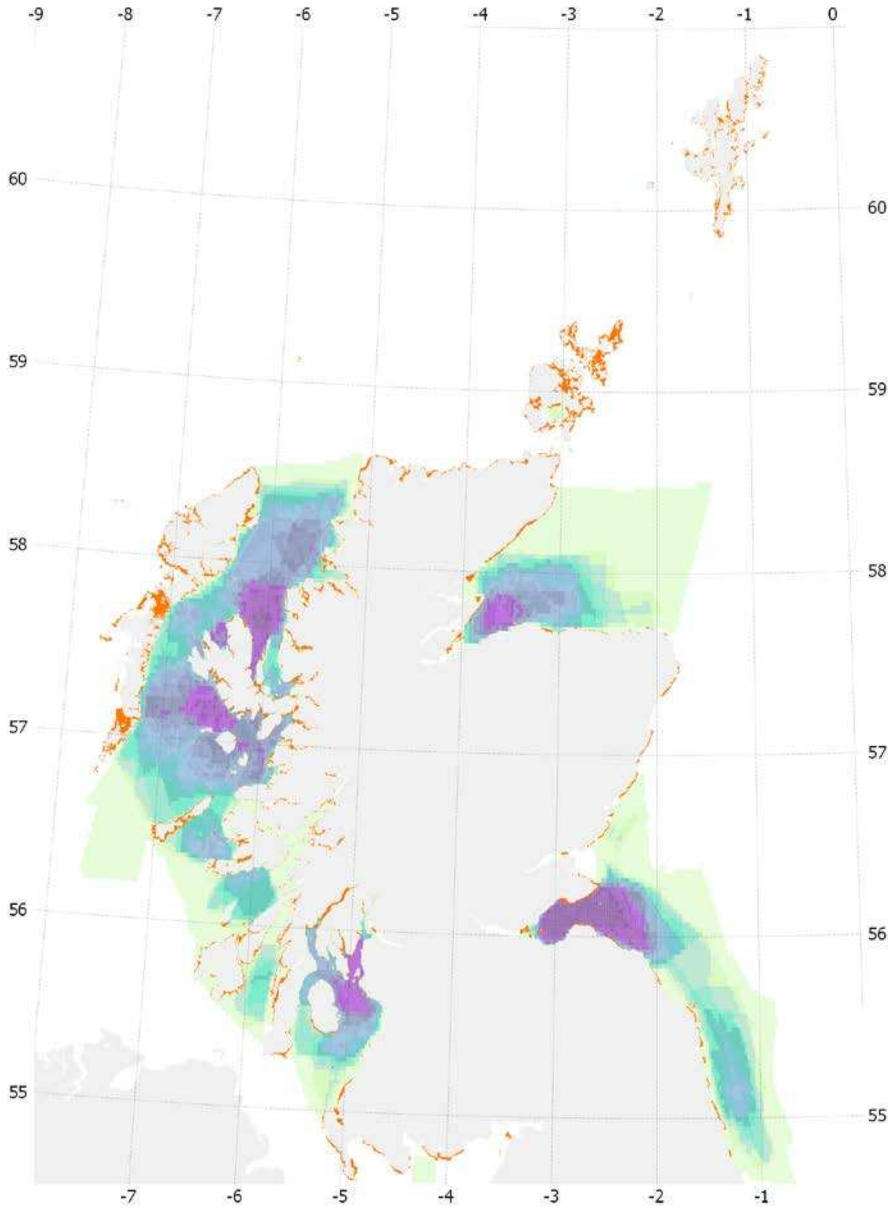


Figure 16. *Inshore fishing locations: trawls where the primary target is* Nephrops

Trawling for target species other than *Nephrops* (Figure 17) is limited on the west coast mainly due to lack of quota for whitefish. Some trawling does take place in the Sound of Gigha and south of Islay. Trawling takes place on muddy to sandy ground and would generally avoid dense kelp due to risks of entanglement and damage to gear from rocks. This fishery is not likely to be directly impacted by kelp harvesting.

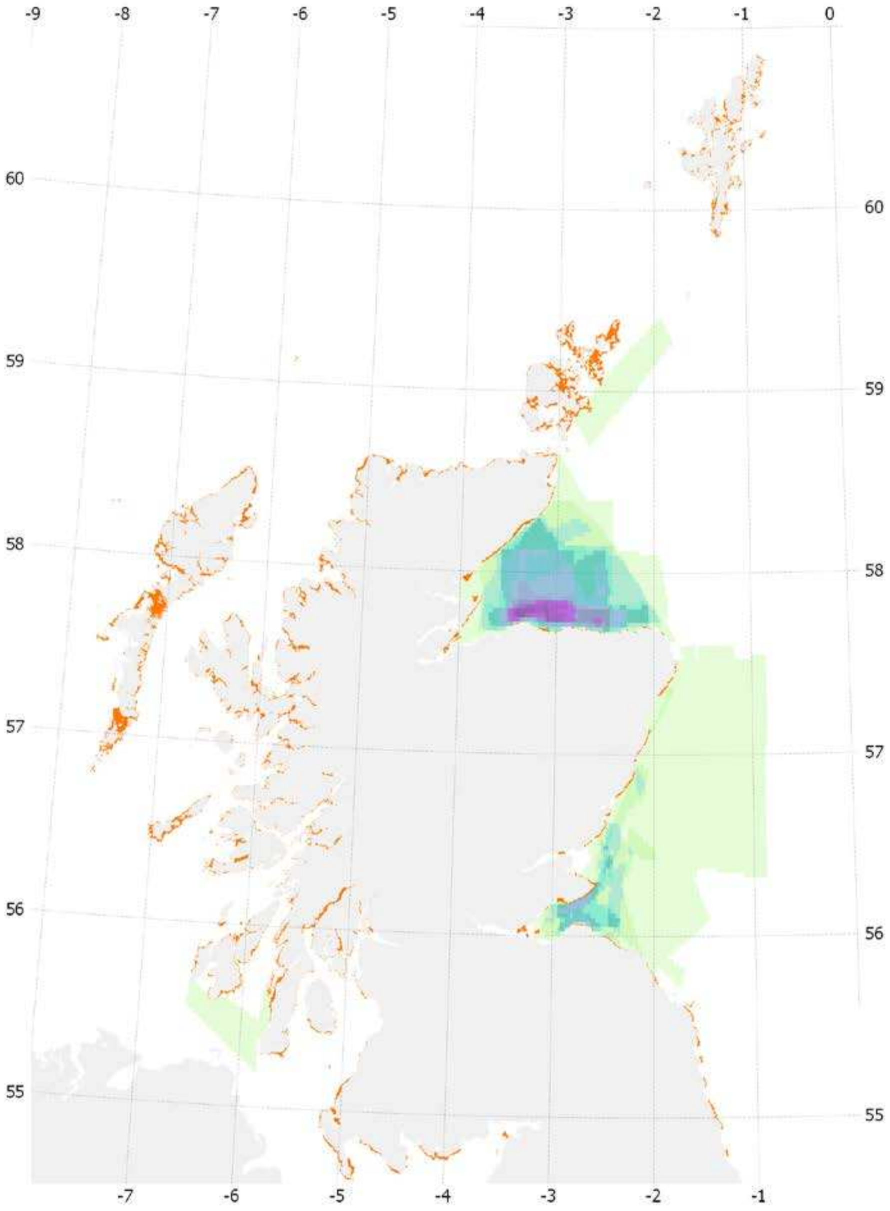


Figure 17. *Inshore fishing locations: trawls where primary target is mainly squid, haddock, plaice or other flatfish i.e. not* Nephrops

Creeling for *Nephrops* takes place all around the Scottish coast (Figure 18). This activity is unlikely to be directly impacted by kelp harvesting because *Nephrops* live in muddy habitats that are unsuitable for kelp. This fishery is not likely to be directly impacted by kelp harvesting.

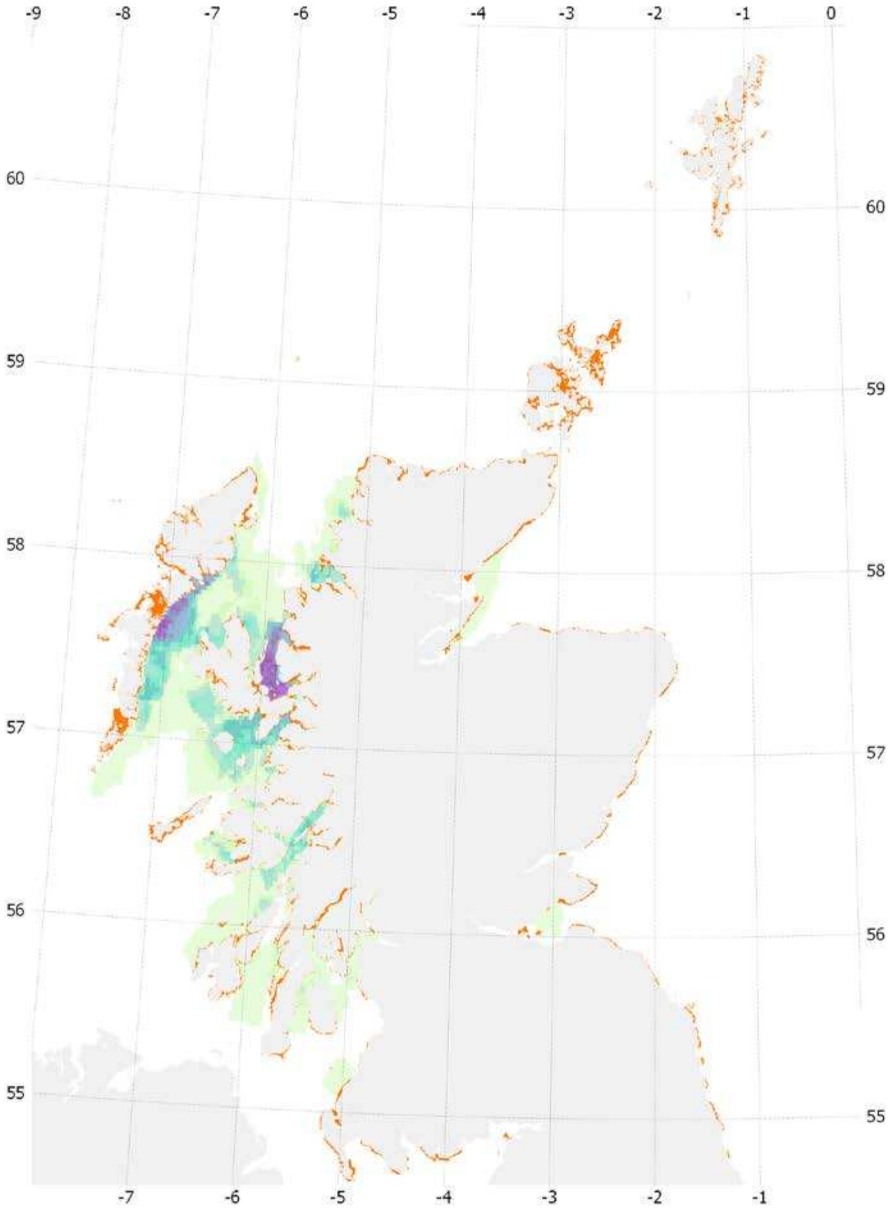


Figure 18. *Inshore fishing locations:* Nephrops *pots (green 1-5, blue 6-14, purple >15) from the Marine Scotland ScotMap project*

Scallop dredging (Figure 19) takes place primarily on sandy ground, although sometimes close in to rocky reefs. Areas of kelp would generally be avoided. This fishery is not likely to be directly impacted by kelp harvesting.

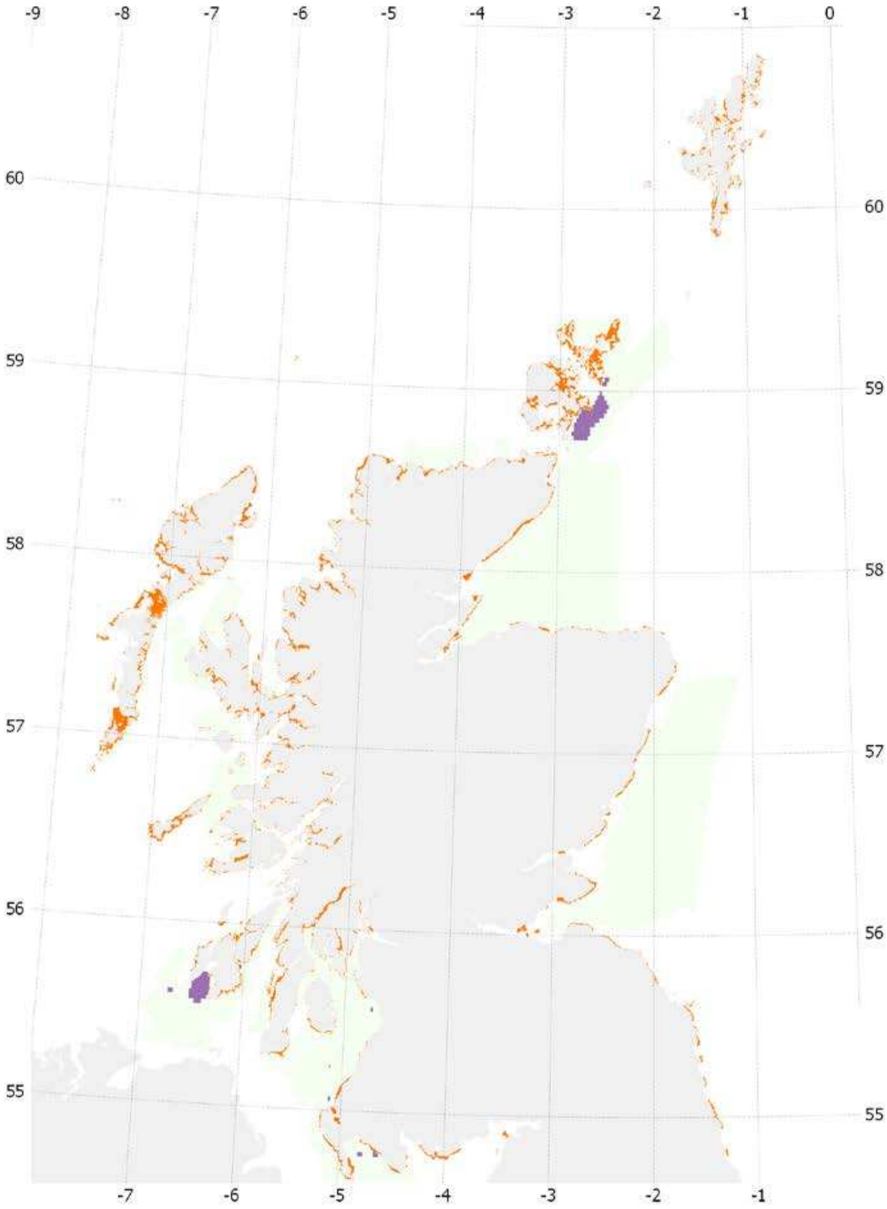


Figure 19. *Inshore fishing locations: towed where the primary target is scallops.*

Scallop diving takes place all around the coast of Scotland, with some hot spots of activity in places such as the Sound of Raasay and in the Orkneys (Figure 20). Scallops are collected primarily from sandy ground, but this can consist of small patches within rocky reef areas. Scallop diving could potentially be impacted by medium- to large-scale kelp harvesting. More detailed local information would be needed to assess the likely spatial overlap and impacts.

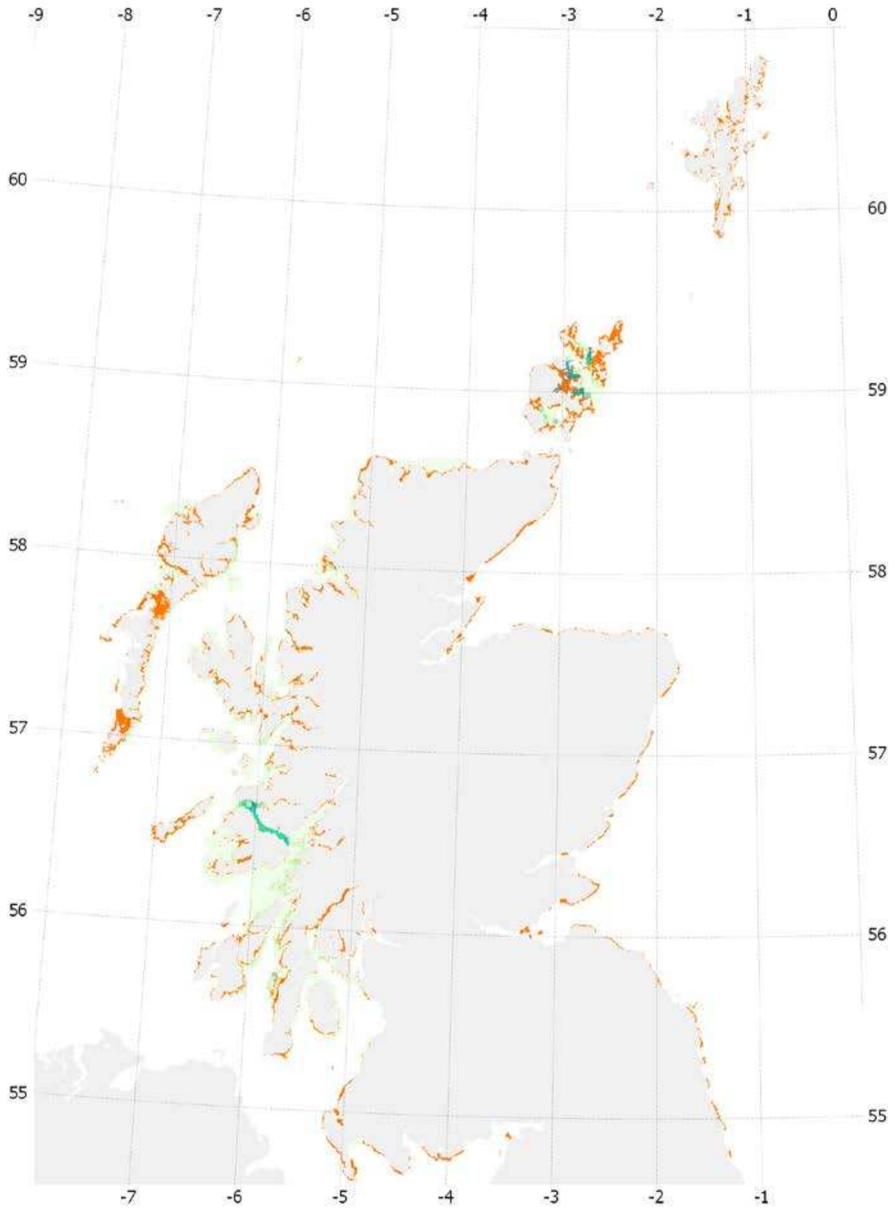


Figure 20. *Inshore fishing locations: scallops taken by diving*

Fishing for mackerel using hand-lines takes place exclusively off the Scottish east coast (Figure 21), well away from the main kelp resources. This fishery is not likely to be directly impacted by kelp harvesting.

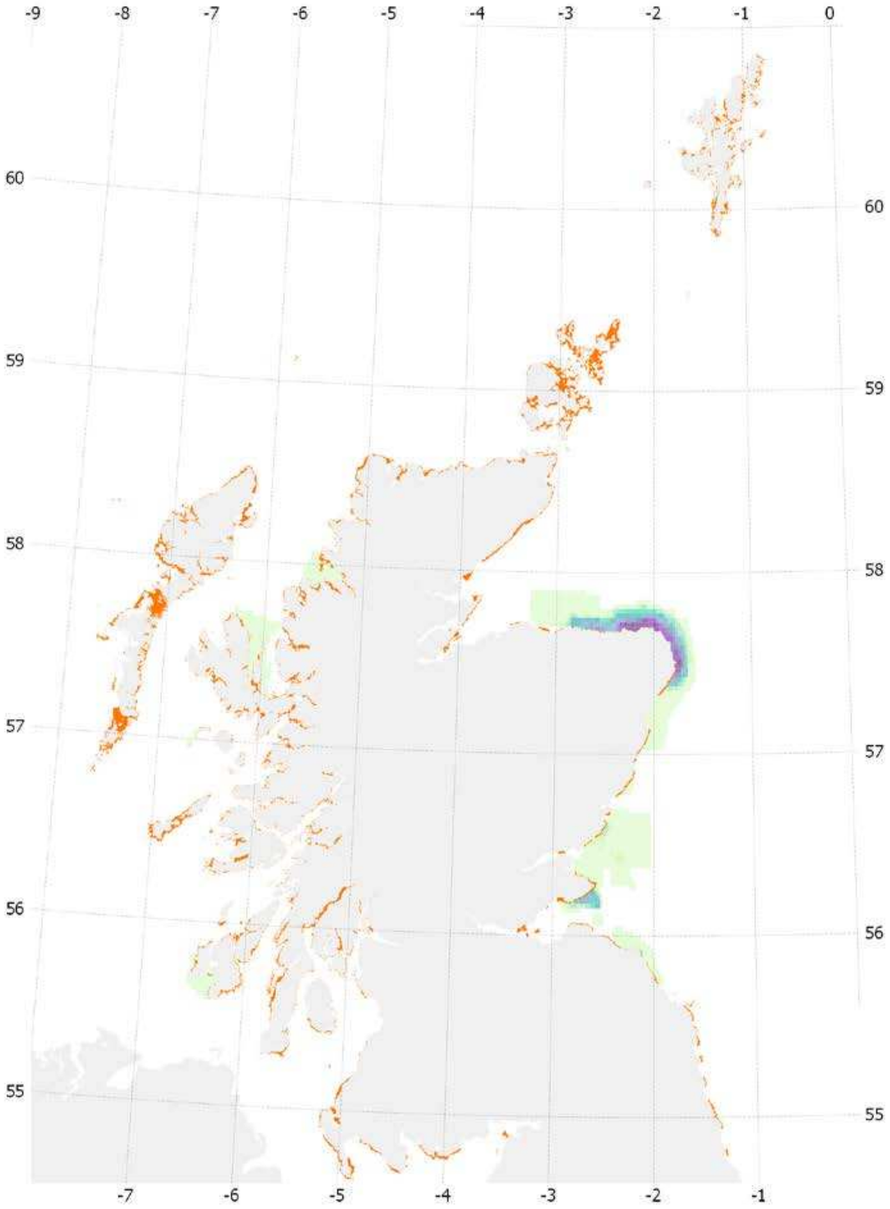


Figure 21. *Inshore fishing vessels with mackerel lines (green 1-5, blue 6-28, purple >28) from the Marine Scotland ScotMap project.*

Scotmap did not cover Shetland because detailed inshore data has been collected there by the North Atlantic Fisheries College (NAFC) in relation to marine spatial planning and inshore fisheries management projects. The locations of important creeling grounds around Shetland can be found at http://marine.gov.scot/information/inshore-fishing-shetland-shellfish-dedging-and-creeling-grounds-oscp and on the National Marine Planning Interactive website.

Overlaying the Shetland data with the modelled habitat where kelp is likely to occur (Section1 from this report) shows potential spatial overlaps, particularly with crab and lobster potting grounds along the western Shetland coast (Figure 22). These fisheries could be directly impacted by medium to large-scale kelp harvesting.

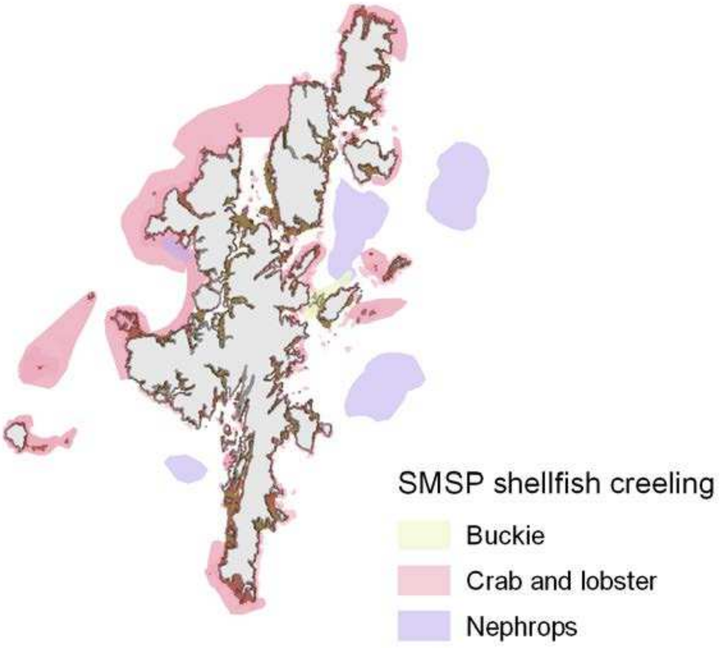


Figure 22. *Inshore fishing and shellfish creeling areas from the Shetland Marine Spatial Plan. (http://www.nafc.uhi.ac.uk/research/marine-spatial-planning/shetland-islands-marine-spatial-plan-simsp/download-marine-atlas-data/)*

Medium to large-scale harvesting of kelp could however impact all these inshore fishing activities indirectly due to increased vessel traffic in ports. Unloading of kelp at times when other fishers want to land their catches could potentially clog offloading facilities and lead to conflict.

Increased vehicle traffic (e.g. kelp transporting lorries) within fishing ports might also be another factor which would need careful planning in relation to conflicts with transport of more traditional fishing products.

Wildlife tourism and recreational diving are other, non-fishing, sectors that could be negatively impacted by the development of large-scale kelp harvesting. Evaluation of these impacts would require studies of the extent to which the recommended harvest sites are currently used for these activities and what the potential impacts would be.

Recreational angling could be potentially affected, although anglers generally avoid deploying fishing tackle within dense kelp beds due to the risk of entanglement. However, anglers often fish from rocky shorelines which are likely to be close to kelp beds and may target species often associated with kelp beds, such as pollack (Section 3.4).

Although overall valuations of recreational diving are available for Scotland at regional scales (Marine Scotland 2016a), local-scale studies would be needed at sites where kelp harvesting is being considered.

Finally, other sectors such as tourism might be impacted by waste from harvesting, such as broken stipes and other material lost during harvesting. Build-up of waste in some places appears to have happened in Norway (https://www.youtube.com/watch?v=hEIAlBFjdCQ).

3.11 Implications of Kelp Ecology for Management

- The reproductive biology of the kelp species needs to be considered because differences between species will affect their ability to recover from harvesting.
- Seasonality and reproductive periods vary across different kelp species and should be considered in the frequency and duration of harvesting activities. The general reproductive periods for European kelps are September or October-April for *Laminaria hyperborea* with the other species (*L. digitata, Saccharina latissima, Saccorhiza polyschides, Alaria esculenta*) tending to reproduce in the autumn through early winter.
- Height of removal needs to be considered, according to the species being harvested, as there are different implications for the future reproduction of the plant.
- Kelp experience a range of hazards throughout their life cycle and assessment of impacts of harvesting would need to be considered in addition to these.
- Areas selected for harvesting need to be assessed for their role in provision of critical services, including habitat for epifauna, fish, birds, mammals and any coastal erosion protection role that kelp habitats may provide.
- Kelp may have a role in coastal protection, so harvesting should avoid orientating harvest strips in the direction of prevailing currents to the coastline, or removing all kelp around the low water mark.
- It is recommended that kelp harvesting in Scotland follows the practice in Norway, with sector-based management in which sectors are open for one year followed by four years' fallow until the next harvesting period.
- It is recommended that kelp harvesting practice in Scotland follows the Norwegian model of harvesting in strips one nautical mile wide such that no strip borders one that has been previously harvested. If sufficient kelp habitat is available, each

harvested strip should be bounded by permanently fallow (unharvested) strips to ensure proximity to intact forests.

- Given a five-year cycle and 15-20% extraction efficiency, to achieve a target value of maximum sustainable yield in tonnes per year, the management area should cover an area approximately 33x larger than the area estimated to contain that amount of kelp for a given biomass density.

4 GIGHA HARVESTING AREA: MANAGEMENT AND MONITORING RECOMMENDATIONS

In order to illustrate the general principles for sustainable kelp harvesting, a proposed harvesting strategy for Gigha is outlined here. This strategy is based on current kelp harvesting practices as used outside of Scotland. The following strategy should not be considered as a substitute for a complete pre-harvest assessment and the full development of a local exploitation plan.

For this case study, the quantity of kelp and recommendations for exploitation and monitoring of the resource are considered for an area on the west coast of Kintyre around Gigha, and extending along the coast to the north and mainly south of the island (Figure 23). A 34.4 km north-south by 19.0 km east-west box was arbitrarily created to encompass a large area predicted to be suitable for kelp. This box represents a total area of 653.6 km^2, of which 331.3 km^2 is seabed and 319.5 km^2 near rocky intertidal areas.

4.1 Whole-Area Biomass Estimates from Large-Area Models

Predictive models (Section 2.2) indicated that the case study area has the following potential harvesting area:

- 26.4 km^2 where *Laminaria hyperborea* is more than likely to be present
- 10.8 km^2 where *Laminaria hyperborea* biomass may be more than 5 kg/m^2, with larger areas where biomass exceeds lower thresholds (>1kg/m^2, 75.6km^2; >3kg/m^2, 46.7km^2).
- *Saccharina latissima* has 11.9 km^2 where the species is more than likely to be present,
- However, there is only 2.3 km^2 above a biomass threshold of 1 kg/m^{2,} and no habitat above a 2kg/m^2 threshold.

Deployment of harvesting gear may be uneconomic below as yet unidentified biomass densities, so areas with low predicted biomass values may be not be worth considering as available to the resource. The model predicted a total of 352 000 t in the area for all densities of *Laminaria hyperborea* but only 61,000 t in areas where the biomass is predicted to exceed 5 kg/m^2. Greater totals exist for lower thresholds (138,000 t >3 kg/m^2; 203,000 t >3 kg/m^2; 322,000 t >1 kg/m^2). The potential harvesting area is predicted to support much lower tonnages of sugar kelp, *Saccharina latissima* (34,000 t >0 kg/m^2; 2,800 t > 1 kg/m^2) even at the lowest thresholds.

4.2 Acoustic Survey Biomass Estimates and the need for Finer Scale Maps

Without detailed data on the presence of suitable rock surfaces, model-estimated biomass values may be higher than actual biomass. Surveys completed in this area as part of this project showed that kelp was rare or absent from the two most northern (Rhunahorine Point and Gigha Island) of the four areas surveyed using acoustic and video techniques, despite these areas being predicted by the model as suitable for kelp. These two areas were mainly soft sediment and with seagrass and algal turf instead of kelp (see Envision Survey Report in Annex B). This highlights the issue that available seabed habitat maps do not necessarily capture the fine-scale spatial heterogeneity which may exist at a site.

The acoustic surveys returned values for percentage volume inhabited (PVI) across small areas (1.2 km x 0.5 km) of seabed (see Annex B). PVI values of 10 correspond to 3.2 kg/m^2 and 20 to 10.8 kg/m^2 (Blight et al. 2011). Maps based on PVI scores suggested that kelp beds are more variable at scales less than the 200 m of the large-scale model, and that modelling or mapping at the 5-10 m scale may give a smaller estimate of total viable harvesting area and biomass. Small scale patterns in the PVI and inferred biomass appear to fit well with depth contours on local charts. For example, high biomass areas around Cara Island matched the 5m contour.

It is therefore recommended that pre-harvesting surveys are made at finer scales using the acoustic and video drop-down method. If fine-scale bathymetry is available, either from local multibeam or other surveys, the association between PVI and depth and bottom type may be used to produce a more accurate operational map of biomass distribution. Such surveys will benefit any harvester in not only identifying exactly where the kelp resource is located, but will give a more accurate picture of potential yield, and will can act as baseline data measurements for monitoring purposes.

4.3 Harvesting

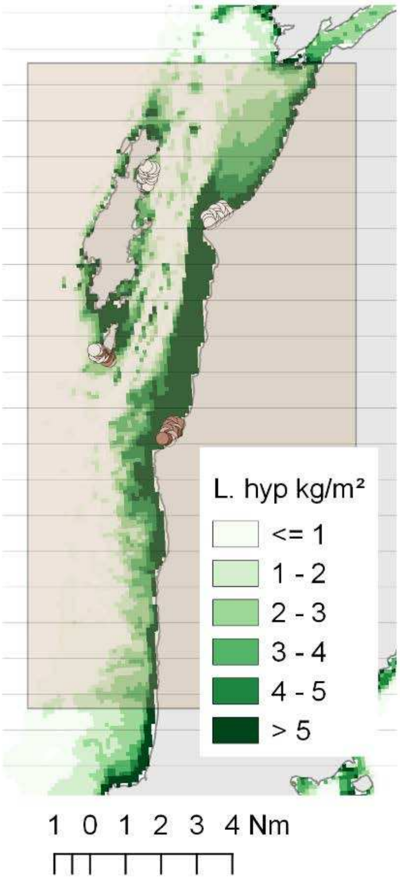


Figure 23. *Predicted* Laminaria hyperborea *biomass around Gigha in a potential harvesting area. Horizontal grey lines show the division of the area into one-nautical-mile 'fields' for harvesting.*

Harvesting in Norway follows the practice of managing 'fields' that are one nautical mile (1.85 km) in width extending out from the shoreline as far as the kelp forest extends (Werner & Kraan, 2004). Fields are harvested on a five-year cycle such that no field harvested is bordered by one that has been harvested in previous years. Typical extraction removes 15-20% of biomass from each field. Under this management scheme, 20% of kelp biomass is removed from one fifth of the potential harvesting area per year, which would result in an annual yield of 2,400 t of kelp from a total harvestable biomass of 60,000 t., If the harvesting vessels collect and land 20 t per day (Table 17) and operate for 100 days a year (Section 5.4.3), this suggests that an area of this size may support little more than a single vessel (2,400 t / 20*100 = 1.2 vessels).

Notwithstanding a gap in the current scientific research into the potential impacts of kelp harvesting, the Norwegian model appears to be able to allow recovery of kelp standing stock over time. Harvesting too much kelp is likely to result in lasting damage to the kelp habitats, with lower annual yields received in future years**. It is recommended that any harvesting activity follows the Norwegian model of spacing of harvesting activity and at least a five-year cycle of harvesting and recovery** (see Sections 3.6.1, 3.7.1)**.**

4.4 Monitoring

After the pre-harvest surveys of available resources it will be necessary to monitor the recovery of impacted areas and to assess the status of recovering stocks. Kelp habitat monitoring methods are outlined in Section 3.9 (Table 8) and should be used in a pattern that reflects the harvesting practice ultimately adopted. The whole area should be assessed at least every five years using acoustic and video approaches similar to those used in this report. It will be possible to get a broader view of the kelp resource by adopting a less spatially intensive acoustic sampling track by setting a single course through the primary areas for harvesting, with a spacing of 1 km or so between tracks. In addition to looking at the whole area, smaller representative areas (n=3) of unharvested/recovered beds and 1 to 4 years' post-harvest beds should be assessed each year to track rates of recovery of kelp in the area. These targeted surveys may be supplemented with data collected during the harvests (yields per day / harvest locations / acoustic bed assessments). Monitoring reports should be submitted to an independent panel (or other body) for regular (annual) review and making recommendations to the licensing body for continuation of the licence and any changes needed to harvesting practice. The licencing authorities may also require additional monitoring of impacts of kelp harvesting on kelp associated communities.

Depending on the results of the monitoring studies, the harvesting values may need to be adjusted. For example, if poor recovery is shown over time, then the five-year harvesting cycle may need to be extended into six or seven years, or lower biomass percentages cropped from each 'field'. If recovery is found to be faster than anticipated, harvesting cycles may be reduced in time, or biomass percentages increased. It is likely that there will be site by site and annual variation to kelp recovery, so the monitoring has to provide data that can inform decisions gates built into an adaptive management plan for the area.

Based on the estimated costs of various monitoring techniques given in Table 8, the costs of proposed monitoring programme outlined above for the Gigha area has been itemised in Table 9 below. The costs associated with 'Pre-harvest survey of available resources' is essentially the cost to obtain data necessary for a Licence application (£25,000). However, it is likely that a harvester will already be looking to undertake a similar body of survey work to assess the kelp resource at a given location in terms of the potential viability and returns from the site. One carefully planned survey will provide the data for both purposes. Likewise, monitoring is not only a method of looking at potential impacts, but will also help guide a harvester be more efficient by highlighting how stock is recovering.

Table 9. *Estimated costs for a monitoring programme based on the Gigha Harvesting Area*

		Unit costs (£)	Duration (days)	Total
Pre-harvest surveys of available resources				
	Whole-area biomass estimates from large-area models	£800.00	2	£1,600.00
	Acoustic survey biomass estimates	£1,500.00	7	£10,500.00
	Video and grab surveys	£1,500.00	7	£10,500.00
plus	Small scale model projections using available high resolution bathymetric data, integrating survey data	£800.00	3	£2,400.00
	Total			***£25,000.00***
Five-yearly whole area surveys				
	Acoustic survey biomass estimates	£1,500.00	7	£10,500.00
	Video and grab surveys	£1,500.00	7	£10,500.00
	Small scale model projections using available high resolution bathymetric data, integrating survey data	£800.00	3	£2,400.00
	Five-year review report	£800.00	3	£2,400.00
	Total			***£25,800.00***
Annual assessment of recovery in representative areas				
	Video surveys: 3 harvested + 3 unharvested/recovering areas	£1,500.00	4	£6,000.00
	Model updates of biomass and preparation of assessment reports	£800.00	4	£3,200.00
	Total			***£9,200.00***
Costs over five years				
	Pre-harvest surveys of available resources			£25,000.00
	Five-yearly whole area surveys			£25,800.00
	Annual assessment of recovery in representative areas		4	£36,800.00
	Grand Total			***£87,600.00***
	Total excluding initial survey			*£62,600.00*
Costs per year				£12,520.00
Annual harvest			2400 t	
	Cost per tonne harvest, after setup costs			£5.22

4.5 Additional Activities Required to Complete a Licence Application

In order to be in a position to submit an application for a licence to harvest seaweed, a developer will have to undertake a number of steps in addition to conducting a baseline survey to characterise the natural environment of the area of interest. These steps are discussed in detail in Section 5 (following), but a summary is included in Table 10 below. Some of these steps should be undertaken before characterisation surveys are conducted, as the outcomes may influence the viability of conducting harvesting at a particular site

Exact daily rates, times taken for each activity and final costs involved in completing the necessary steps for a licence application will vary according to the salary and overhead costs of the businesses involved, the complexity of the issues raised by the Environmental Report, the distances required to travel to local stakeholder meetings and the potential costs of overnight stays in the local area following such meetings. Public consultation meetings and public notices will need space to be bought in local newspapers and may require notices to be posted locally at prominent sites. Thus, no daily rates are given in Table 10, nor are any costs provided for likely items of expenditure, but the Table does provide a basic reckoner for collating such costs. The cost of pre-harvest surveys (from Table 9) is included.

The duration of each of the separate activities is estimated as a rough guide but is likely to change depending on local circumstances, the size of the planned harvest and other business- and location-specific variables.

Table 10. *Cost calculator for a hypothetical licence application for the Gigha Harvesting Area. Full descriptions of each activity are given in the Sections indicated in this report. *** denotes where costs cannot be estimated with any degree of accuracy due to their variable nature (see Section 4.5)*

Section	Activity		Likely costs		
			Daily costs	Duration (days)	Total
5.2.1	**Scoping**				
	Engagement with licence granting bodies, local stakeholders, statutory consultees. Production of a scoping report	Discussions with Marine Scotland, Scottish Natural Heritage etc.	***	6	***
		Meetings with local stakeholders: 1 public meeting	***	3	***
		Meetings with local stakeholders: email and telephone conversations	***	5	***
5.2.2	**Environmental Appraisal**				
	Pre-harvest surveys of available resources	(from Table 9)	-	-	£25,000
	Commitment to monitoring impacts	Preparation of Environmental Monitoring Plan	***	5	***
	Consideration of Habitat regulations, European Protected Species, Priority Marine Features, Invasive non-native species, and other users of the proposed area. Planning for mitigation activities.	Production of Environmental Report	***	15	***
5.2.3	**Application**				
	Issuing public notices	Local press, signage	***	3	***
	Submission and correspondence				
				Total	***

5 PLANNING AND MANAGEMENT OF INDUSTRIAL KELP HARVESTING IN SCOTLAND

5.1 Introduction

Industrial harvesting is a new sector in Scotland and has yet to be considered specifically in policy, legislation and guidance applying to marine activities. In response to applications so far, it has been interpreted in relation to the regulatory framework and the steps required in order to license such activities are set out below (Section 5.2). This clarifies the legal requirements to be addressed in an application by an operator proposing to undertake vessel-based seaweed harvesting in Scotland.

While the steps of the licensing process are relatively straightforward to set out, with a clear underpinning regulatory framework, there is some flexibility in how these requirements can be addressed. Approaches can develop over time, in response to new understanding, and depend on action, consultation and agreement between key stakeholders, primarily the industry, Marine Scotland, statutory consultees and Crown Estate Scotland.

This section therefore presents an overview of the requirements to obtain a licence for seaweed harvesting, and also identifies ideas to be considered in the developing planning and management of the sector (Section 5.3). At this early stage of sector development, it is difficult to predict how the planning and management of the sector will evolve, since it is contingent on the developing understanding of the benefits and risks of the sector, and the extent to which its expansion is seen as feasible and desirable by the primary stakeholders.

This section was informed by review of written advice provided by Marine Scotland Licensing and Operations Team (MS-LOT), Scottish Natural Heritage (SNH) and the Scottish Environmental Protection Agency (SEPA) on applications received to date, information set out in the Strategic Environmental Assessment (SEA) on Wild Seaweed Harvesting (Scottish Government, 2016) and through discussion with MS-LOT, Marine Scotland Science (MSS), Marine Scotland Planning and Strategy, SNH and Crown Estate Scotland.

5.2 Current Licensing Process for Seaweed Harvesting in Scotland

The current licensing process is set out here, to enable an understanding of what information needs to be provided, and what needs to be considered in developing an application for a licence for vessel-based seaweed harvesting. These steps are broadly applicable to offshore activities and do not represent comprehensive guidance for the sector, and there are numerous other sources of information available on approaches to impact assessment and the regulatory framework. This section instead presents an overview of the key steps and general requirements of the licensing process, and to support wider discussion on *how* these requirements could be addressed.

For industrial harvesting utilising mechanised techniques, there is the potential for significant adverse effects to occur, as identified in the SEA undertaken for the activity in 2016. The use of vessels for this activity means that a licence from MS-LOT is required under the Marine (Scotland) Act 2010, since it constitutes the use of "*a vehicle, vessel, aircraft, marine structure or floating container to remove any substance or object from the seabed within the*

Scottish marine area" as per Section 21 (1) 6 of the Act (seaweed has been deemed a 'substance or object' in this context). A marine licence application is therefore required for all such proposed activities, with a supporting assessment of environmental effects, proportionate to the scale of proposed activity.

While formal Environmental Impact Assessment (EIA) is not required for vessel-based seaweed harvesting activities, an assessment of effects by an applicant is required to support the application for a marine licence, which must be determined with regard to the need to protect "*the environment, human health and legitimate use of the sea*." Following a similar process to EIA therefore provides a logical way to scope and appraise the effects of potential harvesting activities, with the scale of assessment dependent on the scale of proposed activities and likely sensitivities. For this, the term 'Environmental Appraisal' (EA) is used in this report to avoid confusion with the formal EIA process, but represents a similar approach.

The key steps of the licensing process are outlined below, providing an overview of the requirements at each stage. As indicated, engagement with stakeholders is critical throughout the process, including statutory consultees and other users of the sea, and beginning early in the process of proposal development.

5.2.1 Scoping

5.2.1.1 Initial notification of intended activity

At the earliest stage, it is appropriate to request a meeting with MS-LOT to notify them of the proposed activities. This would be best supported by a prior written submission containing appropriate detail on the proposed location(s) and scale of the activity to enable the regulator to screen the proposal and agree whether an Environmental Appraisal is required. Given the scope for potential impacts from harvesting at commercial scale, it is highly likely that EA will be required.

5.2.1.2 Pre-application consultation with local stakeholders

Also at an early stage in project development, it is recommended that the applicant engages with other local interests and users, such as commercial fisheries, to understand potential conflicts. It is advisable that a Pre-Application Consultation Report is prepared, in line with the requirements of the Development Management Procedures (Scotland) Regulations 2013.

Social acceptance and addressing concerns of local stakeholders in communities local to the proposed harvesting is a critical part of obtaining a licence and ensuring sustainability of activities. While formal steps are set out to inform a standard consultation process, this may not always be sufficient in addressing stakeholder concerns. Given the increasing emphasis on the role of communities in planning and development, more in-depth engagement may be an effective way to understand local community perspectives and engender social acceptability. Proactive action on behalf of the industry, such as interacting with communities near sites of potential harvesting interest, can give an early indication on whether there are likely to be objections raised to the proposed activity, and key insight on whether the activity is worth pursuing in that area. This approach has been taken by the aquaculture sector, and could develop trust and effective relationships with local stakeholders and minimise the risk of objections to the application process.

5.2.1.3 Engagement with statutory consultees

Early engagement with statutory consultees is essential, enabling them to provide advice on sensitivities in the area of proposed harvesting and their likely requirements with regard to the EA. This is particularly important in obtaining advice on HRA, and what information will need to be provided to inform this process, if required. This engagement should be continued throughout the process of developing the application, along with on-going engagement with other relevant stakeholders.

5.2.1.4 Scoping report

For proposed activities which have been screened and deemed as requiring an EA to support the application for a marine licence, a scoping process is advised. A scoping report sets out as much detail of the proposed operations as possible, the environmental impacts to be addressed within the EA, including the proposed scope of all baseline surveys to be undertaken, and the methods to be used for informing surveys and assessment of environmental effects. This should include consideration of HRA at this stage, identifying sites and species which could potentially be impacted by the activity and to inform a screening decision on whether further HRA work is required. This will be reviewed by MS-LOT and appropriate consultees who will provide feedback and guidance on the proposed EA and supporting activities.

5.2.2 Environmental appraisal

Following the scoping phase, the applicant should have a clear understanding of the issues to be addressed and the information to be provided in the EA**.** The following steps are then required, based on the advice provided by Marine Scotland and statutory consultees.

5.2.2.1 Characterisation surveys

If an EA is required, baseline surveys are likely to be necessary to characterise the environment and inform the assessment of potential effects arising from the proposed activity. The focus of these surveys (in terms of species and habitats to be included) will depend on the location of the activity and potential impacts identified during scoping and would need to be discussed and agreed with Marine Scotland and consultees. It would fundamentally need to include an assessment of the kelp stock, in order to set out its recovery rates and upon which to base a sustainable harvesting plan. Recognising the breadth of potential impacts across ecosystem components (as described in Section 3 and in the SEA), surveys may be required to assess fish, birds and marine mammals, in addition to characterizing the benthic habitats and the kelp stand itself. The scope and methodology for the surveys should be agreed with MS-LOT and statutory consultees prior to commissioning, in order to ensure that the data collected is likely to provide a sufficient basis for predicting effects. Baseline environmental surveys and stock assessments are critical for any successful monitoring to occur. These surveys therefore should be of sufficient scientific rigour to enable independent expert scrutiny of subsequent harvesting effects, upon which any adaptive management plan actions concerning mitigation can be based.

Where monitoring is necessary (to fulfil standard licence conditions or as part of an on-going adaptive management strategy (see Section 5.3.2), it would be cost-efficient to ensure that the characterisation survey is of sufficient rigour to provide a baseline for the assessment of future changes and monitoring of effects. This may be more costly initially, but would establish, for example, a kelp biomass stock assessment upon which to base sustainable harvesting and recovery, supported by monitoring.

5.2.2.2 Description of planned or maximum extent of harvesting operations

Within the EA, it is necessary to describe explicitly the proposed activities, including harvesting methods, vessels, routes, transits and landing locations, amount of harvesting, etc. Where details are not yet known, a project envelope outlining the realistic worst case scenario capable of being consented is required, thus ensuring that the assessment covers the full extent of possible operations, with the likely maximum potential parameters all outlined.

The description of activities may include proposals for phased harvesting operations across a defined wider area (see Proposed Mitigation, below). This would need to be supported with a monitoring strategy to provide evidence of *in situ* recovery times before extending operations into other areas across the site (see Environmental Monitoring Plan, below).

One application, with an accompanying EA, could be submitted for multiple harvesting sites which are in close proximity, if a boundary is defined around the full extent of operations (and with consideration for potential impacts which may occur outside zone). If proposed activities are in locations which are distant from each other, multiple applications with separate EA’s will be required.

5.2.2.3 Assessment of impacts

Based on the proposed activity, assessment of environmental impacts is required to inform the EA, identifying direct and indirect pathways of impact, and the potential magnitude of these. This would address ecological impacts as described in Section 3, the SEA and advice from SNH, to include:

- Kelp stocks, including setting out the potential loss and recovery rate. Modelling is likely required to clarify the recovery rate, and would need to reasonably account for natural variability and storm events.
- Habitat and communities supported by the kelp, including as nursery habitat for commercial fish species, along with higher predators such as birds and marine mammals.
- Indirect impact of harvesting method on the seabed (e.g. discarding of parts of harvested fronds / stipes and stones during collection)
- Hydrodynamic effects and possible increase in wave energy on shorelines, including indirect effects on species and habitats. This may require hydrodynamic modelling, unless the shoreline and coastal receptors are of low sensitivity, or the scale of activity is minor where desk-based appraisal and expert advice may be sufficient.

- Other physical processes such as the impacts of reduced contribution of beach-cast seaweed to the stability of beaches and coastal vegetation growth, and loss of beach cast kelp as a resource for shore birds.

As with all proposed activities, the impacts on protected areas and species need to be assessed for a licence to be granted. The EA must therefore also address potential impacts on Marine Protected Areas (MPAs), designated under the Marine (Scotland) Act 2010 or the Marine and Coastal Access Act 2009, Sites of Special Scientific Interest (SSSIs) and historic MPAs.

5.2.2.4 Habitats Regulations Appraisal (HRA)

Habitats Regulations Appraisal (HRA) will be required where there is potential for the proposed activity to affect qualifying features of Special Areas of Conservation (SACs) and Special Protection Areas (SPAs), as set out in the Conservation of Habitats and Species Regulations 2010 (the Habitats Regulations). It is recommended that HRA is undertaken concurrently with the EA, presenting information necessary to address the specific requirements of the Habitats Regulations. Where the possibility of a likely significant effect (LSE) on these sites cannot be excluded, either alone or in combination with other plans or projects, an appropriate assessment would be undertaken by the competent authority (in this case Marine Scotland), considering the site’s conservation objectives and in compliance with the Council Directive 92/43/EEC on the Conservation of Natural Habitats and of Wild Fauna and Flora (the EC Habitats Directive). In this case, the applicant would be required to prepare a report to inform the appropriate assessment.

The information to inform the HRA and AA is based on that provided for the assessment of impacts in the EA, but the applicant should present this appropriately, in order to specifically address the requirements of the HRA process. This will include assessment of connectivity to protected sites in order to identify potential risks and include indirect effects on protected mobile species including birds and marine mammals. This should also include whether there are potential for effects ‘in-combination’ with other activities.

5.2.2.5 European Protected Species (EPS)

Also under the Habitats Regulations, it will be necessary to consider the potential for impacts on European Protected Species (EPS), which are listed on Annex IV of the Habitats Directive, and include cetaceans and marine mammals.

5.2.2.6 Priority Marine Features (PMFs)

Priority Marine Features (PMFs) also require specific consideration within the EA, with the habitat ‘Kelp beds’ being one of 81 features considered to be marine nature conservation priorities in Scottish waters. While a specific HRA-type process is not in place for PMFs, impacts should be assessed based on the justification for protection and the measures set out in Marine Scotland’s Marine Nature Conservation Strategy (Scottish Government, 2011).

SNH are developing guidance for how to assess impacts on PMFs, and will provide advice to applications. Information to support assessment in the interim can be found in “Descriptions of Scottish Priority Marine Features (PMFs)” (Tyler-Walters *et al.*, 2016).

5.2.2.7 Invasive non-native species (INNS)

The EA should include an assessment of the risk of introduction of invasive non-native species (INNS) and present a method statement which takes account of the biosecurity plans for managing INNS in Scotland.

5.2.2.8 National Marine Plan (NMP)

Scotland's National Marine Plan (NMP) sets out a broad range of policies which should be considered, both in the assessment of effects and the application determination process. This will be further supplemented by policies set out in regional marine planning which is currently being implemented for Scottish territorial waters.

5.2.2.9 Cumulative Impact Assessment (CIA)

Assessment of impacts in the EA will also need to consider potential cumulative effects of multiple activities, to the extent that information is available.

5.2.2.10 Interaction with other users

To address the requirements of the NMP and ensure co-existence with other sectors, it will be necessary to assess the likelihood for interaction with other users and whether there is the potential for conflict. If any significant effects are predicted on commercial fish species, there is likely to be a requirement for an assessment of the effect that this would have on commercial fisheries, and including consideration of any displacement effects, and the socioeconomic impact of this.

5.2.2.11 Proposed mitigation

Based on the information available, activities should be planned for locations of lowest sensitivity, to minimise the risk of negative ecological effects. Where potential impacts are identified in the EA that cannot be avoided through re-location of activities it will be necessary to set out mitigation to reduce the risk to an acceptable level. The SEA sets out a comprehensive review of potential mitigation options to be considered, focussing primarily on temporal management of activities to enable stock recovery and selection of removal techniques. The applicant should set out which mitigation will be implemented to address negative effects.

Given the dynamic nature of kelp and their associated communities and the need to ensure sustainable kelp stock, an adaptive approach which focusses on phased harvesting activities throughout an area, accompanied with a monitoring programme, may be most effective.

5.2.3 Application

5.2.3.1 Public notice regarding proposed works

Although not mandatory, it is recommended that a public notice is set out, following the procedure in the Marine Licensing (Pre-Application Consultation) Scotland Regulations (2013) when the application and environmental report are prepared, immediately prior to submission.

5.2.3.2 Environmental report

Documentation and outcomes of the EA are to be submitted as an Environmental Report, to accompany the application.

5.2.3.3 Environmental monitoring plan

Monitoring of environmental effects will be necessary in order to establish whether the predictions made in the EA were appropriate, and will form part of the on-going management of the stock. Where potential for impact has been identified, monitoring may include the kelp stock, (e.g. with use of tools such as video cameras, echo-sounders, etc.), species including fish, birds and marine mammals, and coastal processes. This will depend on the location and specific activities and techniques to be employed. Monitoring programmes will be proportionate to the risks identified in the EA, and will be set out in licence conditions. Given the dynamic nature of kelp harvesting and stock management, an adaptive approach may be most suitable (see Section 5.3.2).

5.3 Future Considerations in Planning and Management

While the steps of the application process have been outlined above, it is clear that there are a number of actions and activities which can be undertaken to support the development of the sector. This section addresses such considerations in the on-going development of planning and management of kelp harvesting in Scotland.

5.3.1 Strategic actions and constraints analysis

For new sectors, a number of ‘strategic’ actions can support and ease the cost-burden on operators, to facilitate growth of the sector. For example, the marine renewable energy industry has been advanced by co-operation between Marine Scotland and the Crown Estate (working closely with the industry), who developed national and regional planning tools to identify areas preferable for development. These efforts directed developers to particular areas, based on available information, which were then progressed for leasing (with the Crown Estate) and subsequent licensing (through Marine Scotland). The Crown Estate also co-ordinated a series of ‘Enabling Actions’ on behalf of the industry, which aimed to address key knowledge gaps, reducing risk and uncertainty for developers and encouraging investment. Such supportive activities (which continue alongside other forms of support) were in response to the clear political and policy drivers and associated ecological and socio-economic benefits of the renewable energy sector.

While the information contained in this report furthers the understanding of the feasibility of the seaweed harvesting sector in Scotland, it is not yet clear to what extent it is of strategic interest for development in Scotland. Further discussion between the industry and key stakeholders is required to inform whether supportive, industry-wide activity is required, who would lead it, and how it would be funded.

A key next step would include a comprehensive constraints analysis to identify areas of particular interest for harvesting. This would build on the results presented in this report, which address the fundamental question of the location of seaweed resources at scales which are likely to be of interest to the industry. Using a planning system such as the MaRS tool (developed by the Crown Estate and utilised by Marine Scotland in planning for offshore wind and marine renewable energy), this information would need to be overlaid with data available on ecological and social interests (as held in National Marine Plan interactive (NMPi) or at a regional level). This, informed by consultation with stakeholders, particularly statutory consultees and local communities, could guide the industry to areas of lower 'constraint', and reduce the likelihood of challenges in obtaining a licence for the activity. However, the accuracy of such planning is limited by the quality of data and the ability to make judgements on potential effects at a broad scale, and would always need to be interpreted carefully, and supplemented with in-depth local investigation.

5.3.2 Adaptive management

Information compiled in the SEA and presented in this report documents a developing evidence-base to inform future development of site-specific proposals and environmental assessments. This information is not detailed enough to devise specific management controls at proposed project locations, as this relies on detailed information on the proposed activities and an assessment of the environmental baseline at the project location. Building on available evidence, the EA undertaken by the operator would therefore need to provide a specific operational strategy for activities at specific sites.

Recognising the dynamic nature of kelp as a resource in relation to harvesting, an on-going adaptive management approach would be appropriate to ensure sustainable harvesting activities. This would need to be informed by developing evidence, such as presented in this report and the SEA, by industry-led assessment of local ecological conditions at proposed harvesting site and monitoring of effects, and further interaction between authorities and statutory consultees.

The operational strategy could be based upon an 'adaptive management plan' (or AMP), prepared by the applicant, which would be associated with a single marine licence and focus on the management of a healthy kelp stock across an area defined within the EA. The AMP would need to set out the proposed timing of activities within this zone, in relation to stock recovery rates, accompanied with a monitoring plan to assess the status of the stock and to ensure the efficacy of the management strategy.

An AMP would need to consider the following elements:

- **Baseline** understanding of kelp stock and recovery rates, particular to the target species in the area. This would be based upon modelling undertaken to inform the EA, and present an understanding of how the stock is behaving over time.
- **Operational plan**, setting out the parameters of the harvesting (locations, quantity, timing, etc.), and how such measures will ensure the on-going sustainability of the stock. This will be informed by the species-specific aspects of kelp biology, as described in Section 3, and include timing of harvesting in relation to the reproductive cycle and other seasonal changes.
- **Monitoring strategy** with reporting time frames to ensure the on-going health of the stock. Monitoring requires a rigorous baseline, obtained through the characterisation surveys to inform the EA, hence considering the design of the AMP at the earliest

stage of project development and informing the design of those surveys would be most time and cost-efficient.

- **Adaptive actions** should be set out, identifying what operational decisions would be made in response to the reported monitoring. The timeframes for decision making should be set, and should be in agreement with Regulators/stakeholders. The timelines are likely to be aligned with the monitoring programme and associated agreed reporting deadlines.

An AMP would need to be agreed with the relevant authorities and consultees in order to agree effective monitoring strategies including appropriate timing of review of outputs and management responses.

It is important to note the challenges in developing an adaptive management strategy, as while it presents a framework for the on-going and responsive management of kelp stock, it will still be necessary to undertake a thorough EA process in support of the application for a licence, to satisfy regulatory requirements. Where impacts are predicted, particularly on protected sites and features, a licence could not be granted unless there was sufficient evidence presented to reach agreement that negative impacts are not likely to occur. The monitoring and adaptive operational responses therefore form the basis of on-going management within the agreed boundaries of risk of impact, informed by the EA and licensing process.

Since uncertainty around predicted impacts may be high for seaweed harvesting on this scale, reaching consensus on acceptable levels of impact is difficult and may present a significant cost hurdle to early projects. Investment is required in baseline data collection (to characterise the site and understand the ecosystem to enable assessment of potential impacts), prediction of effects (particularly where complex modelling and techniques may be required) and the on-going data collection required to monitor actual effects once the activity is underway to ensure that negative effects do not occur. However, through adaptive monitoring strategies, knowledge will be gained on the effects of the industry, and if information is shared, costs will reduce over time. If there is collective interest in progressing the sector, then collaboration in funding this initial ‘first-mover’ cost outlay, along with supporting scientific studies, would most effectively advance the sector.

5.3.3 Social acceptance

As highlighted above, social acceptance is critical to the development of the sector, as with other expanding sectors. Developing an understanding of the potential impacts, opportunities, ideas and concerns of communities in locations of potential harvesting activity could be a key next step in understanding the feasibility of developing the sector at large scale, in relation to social and economic impacts. More detailed understanding of the demand (or not) for such activity, from a local perspective, would be informative in understanding the potential for the activity to grow. This is particularly relevant given the increasing emphasis on the role of communities and local stakeholders in the planning and management of coastal activities, resulting from the devolution of the Crown Estate’s Assets, the Community Empowerment Act, the Islands Bill and the delivery of regional marine planning. While the implications of such changes are not yet clear, establishing the basis of communication and understanding with key communities may build support for the sector.

Proposals for harvesting and the harvesting activity itself have led to demands from some stakeholders in Norway and Ireland for greater scrutiny of the sustainability case. It has been suggested, for example, that companies may be incentivised to minimise fallow periods that allow full recolonization of associated communities to occur, since a more monospecific harvest yields better raw material for processing. Similarly, lack of effects of harvesting on fish and crabs reported by Steen *et al*. (2013) has been criticised by campaigners on the basis of the low statistical power in the tests used.

Proceeding with harvesting without conducting an EA, even if not formally required by the regulator, can lead to the activity being viewed as controversial by some stakeholders, as recent experience in Bantry Bay, Ireland suggests (Mac Monagail *et al*., 2017).

5.3.4 Regional marine planning

Within the context of more localised planning and management, regional marine planning may present a useful framework for exploring the potential and raising the profile of the sectors' interests regionally. Regional marine planning is progressing initially in the Clyde and Shetland, to be followed by the other nine marine regions, by 2021. Ensuring that the information developed on the locations of likely harvesting areas is considered in the development of regional planning policies within the marine regions is highly advisable. Due to the primary emphasis on engagement with local stakeholders and other marine users, it presents an early opportunity to discuss proposals with other interested parties, to take a forward look and proactively address issues such as potential conflicts, opportunities for collaboration, synergies and multi-use, as well as potential social acceptance issues.

6 ECONOMIC FEASIBILITY OF KELP HARVESTING IN SCOTLAND

6.1 Harvesting Locations and Methods

Current harvesting of kelps in Scotland is relatively small-scale (Table 11). Rockweed (a wrack rather than a kelp) is removed from inter-tidal areas in the Outer Hebrides with harvests up to 15,000 t y^{-1}. The weed is cut either by hand or using a 'lawn-mower' like device carried on a shallow-draught vessel (Figure 24). This type of harvesting is unsuitable for kelps which grow at greater depths.

www.alamy.com - D5P577

Figure 24. *Seaweed cutter operating in the inshore area of the Outer Hebrides*

In France, about 60,000 tonnes of *Laminaria digitata* are harvested annually as a source of phycocolloids. The main harvest region is Brittany. Seaweed harvesting is regulated by the French Government and the National Syndicate of Marine Algae, a group whose members are drawn from the kelp industry (comprised of two companies), fishermen and scientific advisers. Sixty boats are licensed for harvesting of *L. digitata*, which tend to be fishing vessels that are converted to operate a 'scoubidou' cutter for part of the year (Figure 25). This device is considered to be relatively selective, mainly harvesting individuals of 2 years or more (Davoult *et al.*, 2011). Landings of raw material per boat are restricted to 1,000-1,500 tonnes per annum and, on average, 30% of the biomass of a kelp forest is harvested. Because of the short regeneration time for *L. digitata*, there are no official fallow periods although in certain areas the fishers have introduced fallow periods under self-management (Werner & Kraan, 2004).

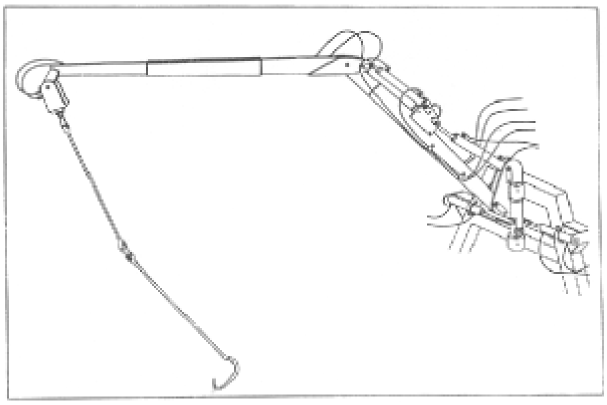


Figure 25. *'Scoubidou' harvesting device as used in Brittany*

Harvests of *L. digitata* increased from 15,000 tonnes (wet) to 30,000 tonnes per annum between 1960 and 1982. Harvest quotas were introduced in response to restricted storage capacities and worries about over-exploitation. The quotas were extended in 1983 and within six years 60,000 t y^{-1} of *L. digitata* were being cut. Since then harvests have been between 40,000 and 60,000 t with a turnover of 1.7-2.7 million euros. Mesnildrey *et al*. (2012) stated that the volume of landings is dictated by the capacity of the processing plants. However, Werner & Kraan (2004) stated that the raw material from this fishery is insufficient to meet demand and that raw material is also imported from countries such as Chile and South Africa. Fluctuations in the amount landed appeared to be more related to the number of vessels operating than to changes in the standing stocks (Davoult *et al*., 2011).

Laminaria hyperborea is also mechanically harvested but using a rake-like device (Figure 26) which uproots larger plants. The annual harvest is of the order of 11,000 t. The rake is fixed to a crane on the boat, and after dragged for around 2 mins which yields around 2 t. The *Laminaria* are delivered directly to companies from boats in Lanildut and a few other smaller harbours. The seaweed is sent by truck to two factories, Landerneau (Dupont-Danisco) and Lannilis (Cargill) for processing (Mesnildrey *et al*., 2012).

Figure 26. *Rake used to harvest* L. hyperborea.

In Norway, about 160,000 tonnes of *L. hyperborea* are harvested annually using seaweed dredges (Vea & Ask, 2011). The Directorate of Fisheries, State Agencies, Research Institutions, fishermen and the industry implement the management schemes. Based on studies by Per Svendsen of the Biological Station at the University of Bergen, Norway in 1972, an initial 4-year harvest rotation was implemented. Following further investigations, this period was increased to a 5-year rotation in 1992 (Vea & Ask, 2011). Harvesting areas are subdivided into smaller fields, which are allowed to be harvested on rotation every 5 or 6 years in most of the country (Vea & Ask, 2011). This results in the removal of between 10-15% of the standing stock. Harvesting is accompanied by monitoring of kelp beds (Werner & Kraan, 2004).

Off California there are 87 administrative kelp beds where commercial harvest is permitted. All commercial harvesters must purchase an annual licence and abide by California regulations. Harvest of kelps increased strongly from the 1930s reaching a peak in the late 1970s of around 160,000 t, but has since declined to very low levels. This decline appears to be due to market conditions and competition from the Far East. A variety of harvest methods are used, for example specially designed vessels with cutting mechanisms on the stern, and a conveyor system that lifts the cut kelp onto the vessel. Blades mounted at the base of the conveyor are lowered 3 feet into the kelp bed while propellers on the bow slowly push the harvester stern-first through the bed. These vessels can collect up to 600 tons of kelp per day. Aerial surveys conducted from June through November are used to direct harvesting vessels to mature areas of kelp canopy that have sufficient density for harvesting.

According to FAO data (FishStatJ 2016 Global Fishery and Aquaculture Statistics database) up to 19,500 t of brown seaweeds (probably mostly *Ascophyllum nodusum*) were harvested annually in Iceland, but only up to 1997. Since then a zero harvest has been reported. Apparently harvesting of *Ascophyllum nodusum* does still take place in the inter-tidal using tractor-based cutters to supply a processing plant owned by Thorvin (www.thorvin.com). A number of other products such as SeaCell fabric, produced by Smartfiber AG based in Germany, can be found on the internet which seem to be linked to kelp harvesting in Iceland. However, no recent peer-reviewed literature on seaweed harvesting in Iceland could be sourced. It is not clear why these harvests are not being reported to the FAO database or what the current harvest quantities are, but they may be rather small in comparison with Norway.

In Ireland, a licence has recently been granted for large-scale kelp harvesting in Bantry Bay but operations have not yet commenced. This licencing has caused controversy because an EIA was not carried out (Mac Monagail *et al.*, 2017).

Kelp are also harvested for non-industrial uses. For example, “The Abalone Farm” (California) has been harvesting giant kelp (*Macrocystis pyrifera*) since 1968 to feed to cultured red abalone (*Haliotis rufescens*). The kelp is harvested using a modified U.S. Navy landing craft with a cutting device and conveyor system mounted on the bow. The harvest rate is around 7 t per day. There are, or have been, similar abalone rearing operations in a number of other countries including South Africa, Australia and Ireland which rely on wild-harvested kelp as feed.

Table 11. *Existing kelp harvesting locations and methods in Scotland, from Scottish Government (2016).*

Saccharina latissimi	Fife; Caithness	Subtidal. Usually harvested in late spring and summer, from boats or by hand at low spring tides. Blades are cut from existing plants, leaving the stipe and lower blade intact and able to keep growing. Juvenile plants are avoided and no plant is removed in its entirety.
Laminaria hyperborea	Fife; Caithness; Loch Sunart (Salen-Glenmore Bay); Ardnamurchan; Bute; Sound of Jura; Summer Isles; Ullapool	Subtidal. In Scotland, *L. hyperborea* is harvested by hand for small scale applications such as specialised foodstuffs.
Laminaria digitata	Fife; Caithness; Loch Sunart (Salen-Glenmore Bay); Ardnamurchan; Bute; Sound of Jura; Summer Isles; Ullapool	Inter/subtidal. In Scotland only manual harvesting at present. Small boats are used to access the plants at low tide, usually by stepping out of the boat to cut the seaweed with a knife. In locations with higher tidal range, it may be possible to harvest on foot. Juvenile plants are avoided. However, *L. digit*ata beds in Scotland are narrow and therefore mechanical harvesting is unlikely to be viable.
Alaria esculenta	Fife; Caithness (Ham-Scarfskerry)	Inter/subtidal. In some areas, harvest is during a narrow window in early summer, after plants have put on reasonable growth but before breaking waves shred the thin leaves. Harvesting is often done by hand and knife at low tide. Juvenile plants are avoided.

6.2 Assessment of Harvesting Vessels

Key Point

- **A comparison of the characteristics of the fishing vessels used in France for seaweed harvesting with the make-up of the Scottish fishing fleet suggests that only a very few Scottish vessels would be suitable for conversion to seaweed harvesting.**

Mesnildrey *et al*. (2012) stated that that the main factor affecting the location of processing factories is proximity to the kelp harvesting areas. Transportation of large volumes of seaweed by road is impractical as transportation costs make the seaweed product uncompetitive compared to the dried products imported from abroad. In France, the main industries working with raw seaweed are located near the main harvest areas. Nevertheless, the French processing industries do still rely on imported dried seaweed when the local resource is out of season. In 2010, imports were of the scale of around 4,500 t from Chile and 3,500 t from the Philippines.

The location of any new processing plants in Scotland would therefore also probably be determined by proximity to the resource which also implies having the means to unload the kelp from harvesting vessels.

The model-based estimates of the distribution of kelp around Scotland were therefore combined with the locations of the major fish landing ports to indicate the proportions of kelp within a range of distances from potential landing ports (Figure 27).

The main ports that have sufficient kelp resources within 20 km are in Shetland (Cullvoe, Lerwick and Scalloway), Orkney (Kirkwall) and to a lesser extent the Outer Hebrides (Stornoway). However, it must be borne in mind that the map only shows the main registered landings ports which relate to quota managed fish and shellfish. These ports have inspection facilities required for fisheries management such as local fisheries officers employed by Marine Scotland but also cold stores, reasonable or good access by road and potentially offloading equipment such as cranes. Table 12 summarises the area of potential kelp habitat found at increasing distances from fishery landing ports.

It might be possible to offload kelp at other minor ports and slipways, for example Barratlantic's facility at Ardvenish, Barra, but this was not evaluated in this report.

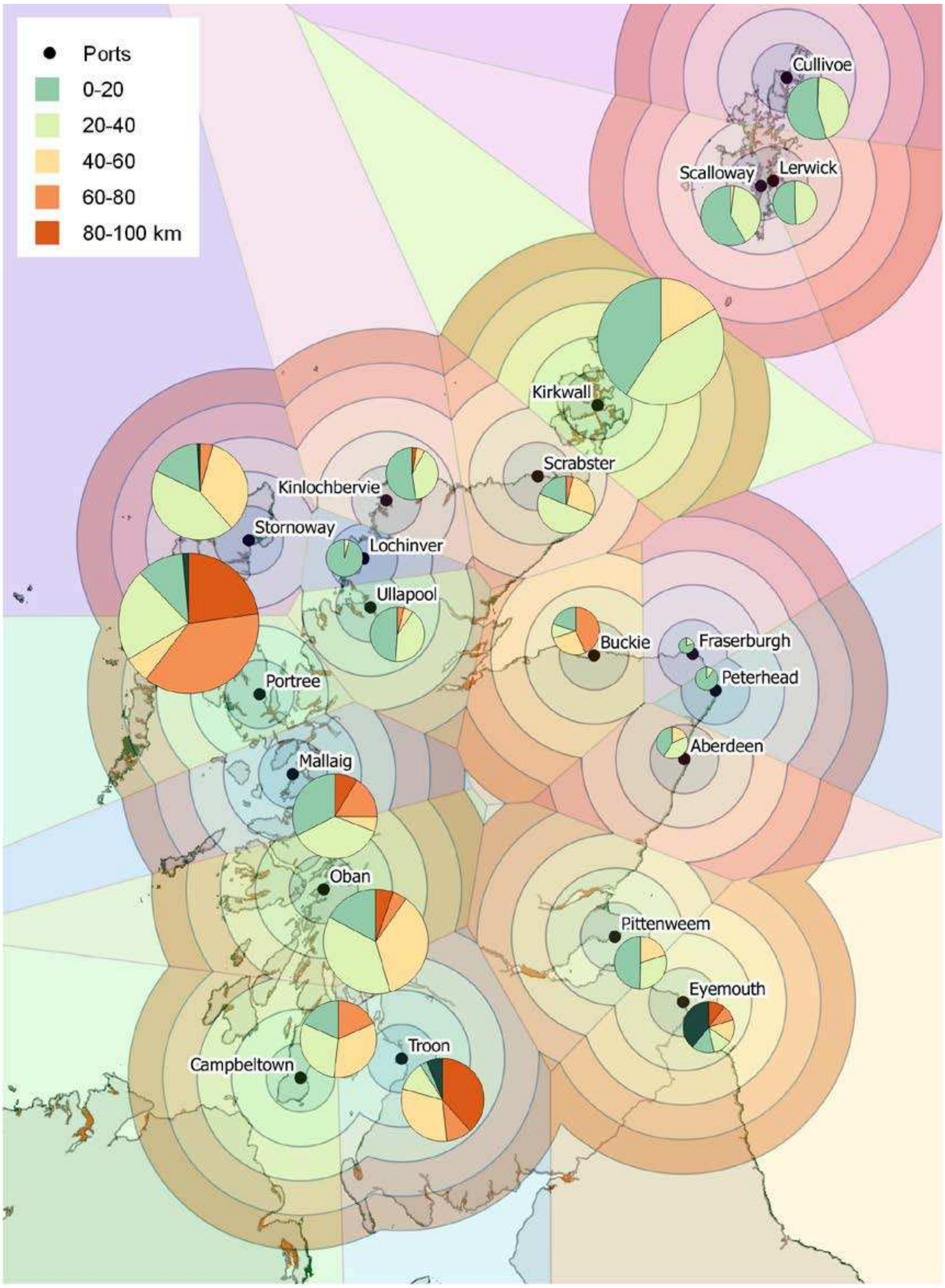


Figure 27. *Kelp habitat extent at increasing distances from fishery landing ports. Bands and pie segments are coloured according to distance, and the size of pies scales to the total habitat within 100 km of each port.*

Table 12. *Area of potential kelp habitat in km^2 habitat at increasing distances from fishery landing ports*

	Area of kelp habitat (km^2) at specific distances from ports (km)							
Port	0-5	5-10	10-15	15-20	20-40	40-60	60-80	80-100
Kirkwall	24.8	58.3	67.2	68.3	221.3	85.3	0.0	0.0
Mallaig	2.2	20.4	15.5	37.0	68.0	11.7	37.9	20.2
Cullivoe	9.0	25.8	16.8	18.6	58.4	0.8	0.0	0.0
Scalloway	8.8	15.0	23.5	22.5	48.7	2.3	0.0	0.0
Portree	3.9	7.4	26.3	32.1	138.4	36.0	250.2	148.8
Oban	1.2	14.8	19.6	19.9	65.0	114.6	15.3	19.7
Stornoway	4.8	24.3	19.3	4.9	135.2	105.6	13.8	0.0
Kinlochbervie	9.8	17.8	9.2	9.1	35.8	4.2	0.0	2.6
Ullapool	7.7	12.7	12.1	13.2	41.5	5.5	1.7	0.0
Lochinver	3.3	3.5	10.4	28.3	1.9	0.0	0.0	0.0
Pittenweem	5.5	7.4	20.8	9.6	27.0	18.4	0.0	0.0
Lerwick	10.7	10.8	6.3	5.7	32.3	0.0	0.0	0.0
Campbeltown	3.9	1.5	13.2	14.9	56.8	62.8	35.3	0.0
Scrabster	5.1	8.4	5.0	1.7	50.7	30.0	4.4	0.0
Peterhead	4.6	1.8	4.1	5.8	2.1	0.0	0.0	0.0
Buckie	3.2	5.2	5.3	1.3	7.1	20.9	31.6	0.0
Aberdeen	4.3	4.1	2.8	2.6	13.5	6.0	0.0	0.0
Eyemouth	1.9	2.3	2.0	2.0	3.8	0.0	0.0	0.0
Fraserburgh	1.4	2.2	0.8	1.2	1.5	0.0	0.0	0.0
Troon	0.0	0.0	1.4	3.2	21.0	65.6	23.0	81.7

In addition to the distance from the port of the standing stock, it is required to know if in the area of harvesting there are the opportune meteorological conditions. From the Marine Scotland Map (Figure 28), along the coastline of Islands and West Highlands, in the areas dominated by the highest quantity of kelp and within a radius of 20 km from the main ports, the average significant mean wave height is within 2 m, making these areas suitable for harvesting (Harald Bredahl, FMC Biopolymer, 2017, personal communication). In addition, specific conditions of wind that facilitate harvesting operations are needed, and in particular average wind speed not exceeding 10 m/s (Harald Bredahl, FMC Biopolymer, 2017, personal communication). Figure 29 shows the average speed as monthly average of the last 10 years (March 2008 to September 2017) at the station of South Uist. With a probability higher than 70% the wind speed is equivalent to Beaufort Scale 4 (6-8 m/s), which has an associated wave height of 1.5 m.

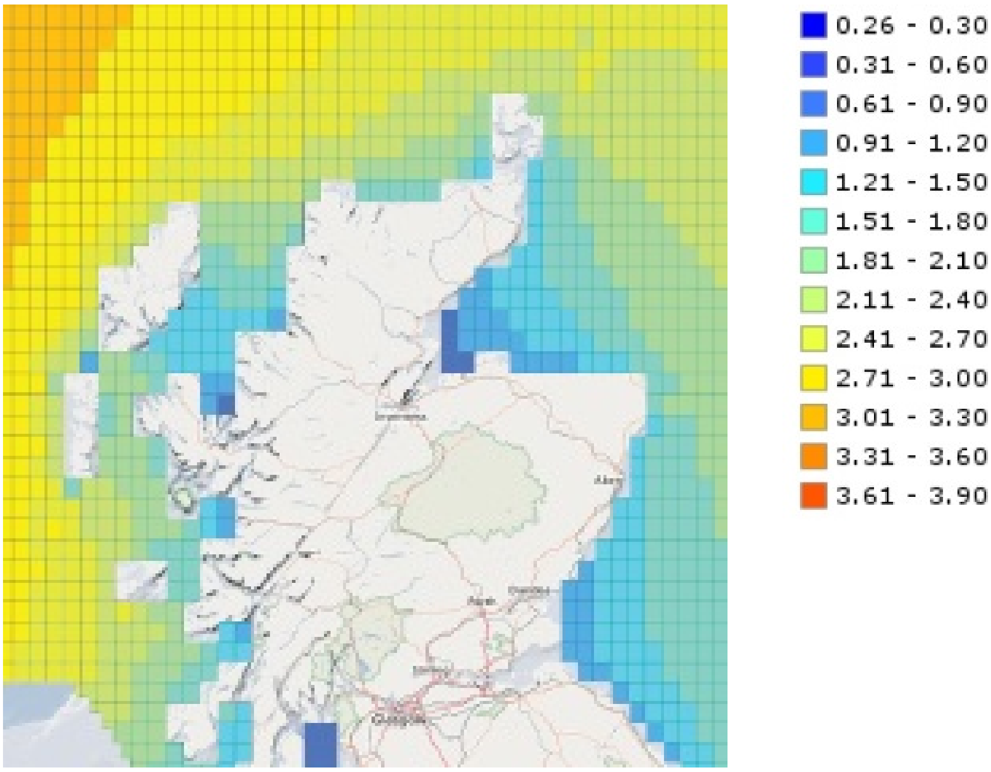


Figure 28. *Annual mean significant wave height (m). (source: Marine Scotland Maps NMPI).*

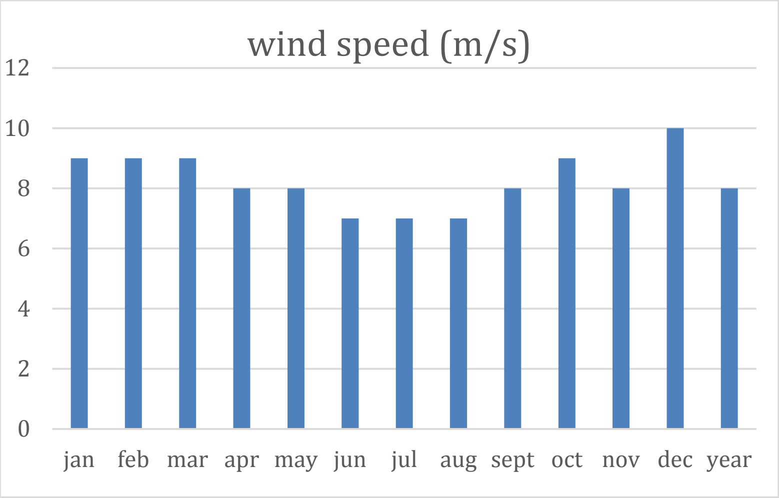


Figure 29. *Average wind speed at South Uist, Outer Hebrides, in the last 10 years (source: https://www.windfinder.com)*

The wind speed for the West Scotland shown in Figure 30 has a similar trend for South Uist, with particular favourable conditions in spring and summer when the average speed is around 10 knots (5 m/s). Although there is some possibility for climatic conditions to be favourable for harvesting during the winter season when the average speed is around 10 m/s, it is expected the bulk of the harvesting to be conducted in spring and summer when the kelp biomass is at the highest level.

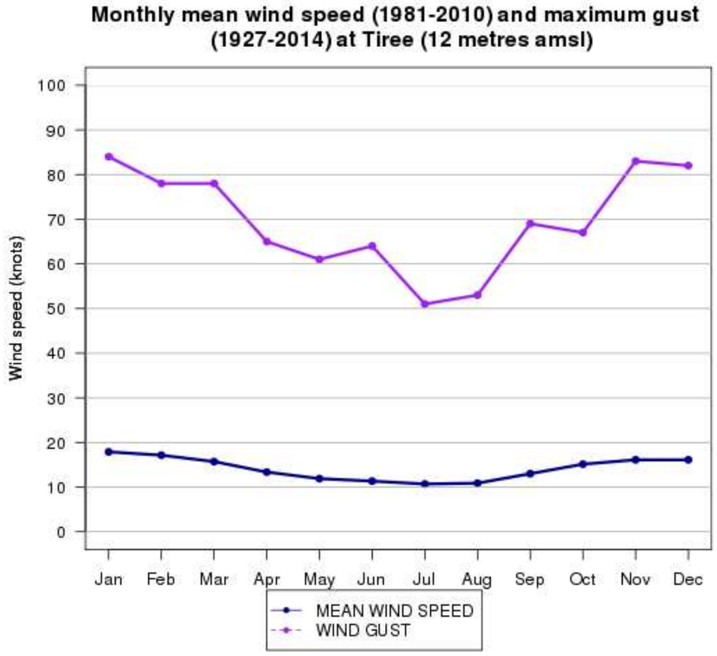


***Figure 30**. Wind speed in West Scotland*

(source: https://www.metoffice.gov.uk/climate/uk/regional-climates/ws)

6.2.1 Scottish fishing fleet and potential for seaweed harvesting

An initial screening of the fishing vessels in the Scottish fleet was undertaken by comparing their characteristics (length, gross register tonnage (GRT) and engine power) with the characteristics of the fishing vessels used for kelp harvesting in France (Table 13).

Table 13. *Comparison between French and West of Scotland, Shetland and Orkney fishing fleet. Information for the French vessel is from Alban* et al*. (2011); information for the Scotland fleet taken from the UK fishing vessel list database (source: UK fishing vessel list database).*

Parameter (average values)	France (year 2008)	Scottish fleet <10 m (year 2017)	Scottish fleet >10 m (year 2017)
Length (m)	10.00	7.39	18.00
GRT	12.10	3.80	127.51
Engine power (KW)	78.00	58.26	376.4
GRT: Length ratio	1.21	0.44	5.39
Power: GRT ratio	6.45	19.12	6.30

The vessels that operate in Scottish inshore waters and might be adapted for kelp harvesting include potters, small- to medium demersal trawlers/dredgers, and larger demersal trawlers/dredgers.

The vast majority of vessels in the Scottish fishing fleet are in the under 10 m category. However, on average these vessels are much smaller in terms of GRT compared with the French kelp harvesting vessels (Table 13) and consequently have smaller carrying capacities. Those vessels <10 metres with specifications similar to the French harvester are mainly located in the West of Scotland (Table 14), and the vessels located in Portree, Oban and Stornoway are also those closest to the most abundant kelp areas according to Table 12. The ratio between average GRT and average vessel length for the French ships is 2.75 times higher than for the vessels in the Scottish <10 m fishing fleet, so the latter would not be expected to be able to transport on average more than 6 t of seaweed (see Section 6.4, Table 27), compared to the 12-15 t loading of the French vessels.

This difference appears to be because the Scottish vessels are designed for transporting relatively low volume high value product, such as *Nephrops*, crabs and lobsters and so have limited hold capacity. Also they are not designed for transporting large amounts of material on the deck. The tendency towards longer less beamy designs for Scottish vessels may also be related to the sea conditions in which these vessels operate.

Analysis of opportunity cost recovery (Section 6.2.2) demonstrates that the smaller carrying capacities of the Scottish vessels creates rather severe constraints in terms of the types and sizes of vessel, the minimum price of kelp and the distance to the resource if these vessels were to diversify into kelp harvesting.

***Table 14**. Locations for Scottish vessels under 10 metre with similar technical parameters to the French fishing vessels (GRT: Length ratio) used for kelp harvesting. Source: UK fishing vessel list database*

Port	Portree	Stornoway	Ullapool	Oban	Lochinver	Cambeltown	Scrabster
Number of vessels	2	2	3	4	2	2	1

On the other hand vessels longer than 10 m would have higher loading capacity, but most have a closed hold or covered working decks that would make loading and unloading kelp problematic. These vessels show a GRT- length ratio larger than 2 and are mainly medium-larger trawlers. A total of 133 vessels have the GRT-length ratio bigger than 4, equivalent to the Norwegian kelp harvesting vessels. Out of these, 10 vessels (Table 15) have also the licence for shellfish and scallops gathering. These are mainly demersal vessels under 24 metres; pots and traps over 12 metres; and *Nephrops* over 250 kW with high operating costs (see Section 6.4) that would require an equivalent catch rate (above 40 tonnes per day) at the highest kelp price of £40 per tonne (as recorded in the French market) to offset the forgone income from fishing.

***Table 15.** Number of Scottish vessels with technical parameters similar to the Norwegian harvester by port*

Port	Ayr	Campbeltown	Mallaig	Scarborough	Scrabster	Ullapool	Kirkwall
Number of vessels	1	1	1	1	2	1	3

Conversely, vessels with a GRT- length ratio between 1 and 2 seem to have a hold suitable for kelp harvest, and correspond to medium size trawlers and potters (10-12 m length). There are 74 (Table 16) of these vessels in the West of Scotland, Outer Hebrides, Shetland and Orkney: this selected fleet has an average length of 11.64 metres, GRT of 15.86 and engine power of 141.18 kW. The fleet also includes larger vessels such as trawler/scalloper (< 15 m) which have been estimated to have the capacity to carry up to 15 t of kelp according to the judgment of Macduff Shipbuilders. The carrying capacity in reality will be strongly related to the vessel design.

Table 16. *Vessels >10 metres with technical parameters similar to the French fishing vessels adapted for kelp harvesting by port (source: UK fishing vessel list database)*

Port	Ayr	Campbeltown	Mallaig	Scrabster	Ullapool	Lochinver	Oban	Portree	Stornoway	Kirkwall	Lerwick	Scarborough
Number of vessels	2	6	1	3	5	1	8	2	7	22	3	14

The information in the above table can be compared with the Table 12, which identifies the ports closest to the most abundant kelp resources within 10 km. The 48 vessels (out of 74), stationed at the ports of Kirkwall, Lerwick, Stornoway, Ullapool, Scrabster and Oban are closest to the most abundant kelp resources, and therefore these ports appear to be the most suitable logistic bases for harvesting.

6.2.2 Conclusions from modelling the feasibility of using fishing boats/vessels for kelp harvesting

The breakdown of incomes from traditional fishing for small- and medium-sized vessels undertaken by Seafish (see Section 6.4, Table 28) suggests that the vessels fall into three groups with similar income levels:-

(1) Potters (<10 m) and Drift/fixed netters (<10 m)

(2) Demersal trawlers (<10 m) and Potters (10-12 m)

(3) Scallopers (<15 m).

According to discussions with MacDuff shipbuilders the load of kelp which the fishing vessels could carry varies between 2.5 -15 t, depending on vessel type and size (see Section 6.4, Table 27). This information was used to estimate the number of kelp harvesting trips each type of vessel would need to make to generate sufficient income from kelp harvesting to offset the income from their traditional fishing activity (Table 17).

For the larger fishing vessels, income data were available for the potters (> 12 m) and scallopers (> 15 m). The number of kelp harvesting trips each type of vessel would need to make to generate sufficient income from kelp harvesting to offset the income from their traditional fishing activity is given in Table 17.

Based on the author's experience typical steaming speeds for medium-sized fishing vessels will be in the range 8-12 knots (12-22 km h^{-1}) which is close to vessel monitoring system (VMS) data for larger fishing vessels analysed in Mills *et al*. (2007). VMS is not carried by smaller vessels which may transit at slightly slower speeds. Some of the more modern potting vessels are designed for higher-speed transits in order to reach, and return from, the fishing grounds more quickly. For calculation of travel times between port and kelp location it was assumed that transit would occur at 10 knots for all vessel types.

It was further assumed that collection and loading of 1 t of kelp onto the fishing vessel would take 15 mins on average. This figure is likely to vary with harvesting technique and vessel size but represents our best guess estimate at this time. The dedicated Norwegian vessels using a rake harvester can collect 1 t of kelp in a few minutes but we think collection time is likely to be slower on a fishing vessel which is not designed specifically for this task. It was further assumed that unloading the kelp after each trip would take an additional 30 mins per trip.

These estimated times were put into a simple model, which looked at the total time it would take for transiting plus harvesting and unloading kelp for different types of fishing vessel working at different distances from the unloading port. The results show that there are major constraints in terms of the time required each day to harvest and transport sufficient kelp to offset the income which would be earned if the vessel was engaged in its traditional form of fishing.

The results show that the vessels which might be able to perform enough kelp collecting trips each day to offset income lost from traditional fishing are at the lower to medium end of fishing income.

In terms of economic and time feasibility Potter and Drift/fixed net vessels (<10 m) which are able to transport 2.5 t of kelp per trip would have to harvest kelp within 15 km of the landing port if the kelp price was £40 t^{-1}. At a kelp price of £30 t^{-1} they need to reach a resource within 10 km of the unloading port whilst at £20 t^{-1} the harvesting is not economically attractive at this transport capacity. If these vessels are able to transport 5 t each trip then they might be able to harvest at up to 35 km from port when the kelp price is high. At the medium price of £30 t^{-1} they need to work within 25 km and at the lower price the resource must be within 10 km of the unloading port (Table 19).

For demersal trawlers or medium-sized potters (10-12 m) there is a potentially viable kelp-harvesting envelope out to 25 km, but only if the price is at £40 t^{-1}.

The highest income small- to medium-length vessels are the scallop dredgers (<15 m). There is a small viability window for kelp harvesting by these vessels providing they can carry 10 t kelp each trip and the kelp price is £30 t^{-1} or above. This carrying capacity is likely to apply only to the larger scallopers (10-15 m). To be economically attractive the resource needs to be within 15 km of the unloading port at the higher kelp price or 5 km at the middle price (Table 21).

For potters (>12 m) there is a small window of viability for kelp harvesting providing they can transport at least 10 t kelp each trip, the kelp resource is within 10-20 km of the unloading port, and they are prepared to work for more than 18 h each day (Table 22).

For large scallopers (>15 m) kelp harvesting is never an economically attractive option, even if the kelp resource is close to the unloading port (Table 23). This is because of the high value of their normal fishing target.

Based on this model, determining whether kelp harvesting could be a feasible diversification option is related to the balance of kelp transport capacity and income generated from the traditional fishing activity. If vessels are able to transport 10-15 t of kelp each trip, then harvesting becomes viable in terms of time up to 30 km from port. However, kelp harvesting will only be economically attractive if the opportunity cost of traditional fishing is relatively low.

Kelp harvesting might be attractive for under 10 m potters and demersal trawlers, but only for those vessels able to transport around 5 t kelp each trip, when the price is £30 t^{-1} or above and when the distance to the kelp resource is 35 km or nearer.

For scallopers (all sizes) and larger potters (> 12 m) kelp harvesting does not appear to be a very attractive option for diversification. This is largely driven by the relatively high-value of their normal catches.

Larger traditional design Scottish fishing vessels may also not be suited to working in the shallow waters where the kelp are located. The draught of vessels would also thus need to be taken into account.

The use of fishing vessels in France to collect kelp appears to be related to their design which allows them to transport relatively large quantities of kelp each trip. The vessels used appear to be relatively wider in relation to their length compared to Scottish vessels and they are also likely to have shallower draughts allowing them to operate safely in the waters where kelp grows. In addition, the resource is relatively close to the processing plants reducing travel time.

Analysis of the economics of harvesting *L. hyperborea* in Norway (Section 6.2; Table 24) suggests that harvesting is more efficient if carried out by custom-built vessels. Although these vessels have higher capital and operating costs they are designed specifically for kelp harvesting and thus have higher transport capacity requiring fewer trips to offset their higher costs as well as being equipped with suitable cranes for collecting and handling the material.

Table 17. *Calculation of the range on number of trips small to medium-sized fishing vessels would need to make each day to offset the income from traditional fishing at different prices for kelp.*

Vessel type		Tonnes kelp needed day^{-1} to offset traditional fishing at kelp price £20, £30 or £40 t^{-1} of kelp from Table 29		
		£20	£30	£40
Drift/fixed netters <10 m		28	19	14
Potters <10 m		26	18	13
Demersal trawlers <10 m		38	25	19
Potters 10-12 m		39	26	20
Scallop dredgers <15 m		71	47	36
	Notional carrying capacity t trip^{-1}	Trips needed day^{-1} to offset traditional fishing at kelp price £20, £30 or £40 t^{1} of kelp		
Drift/fixed netters & Potters (<10 m)	2.5	12	8	6
Drift/fixed netters & Potters (<10 m)	5	6	4	3
Drift/fixed netters & Potters (<10 m)	10	3	2	2
Drift/fixed netters & Potters (<10 m)	15	2	2	1
Demersal trawlers (<10 m) & Potters (10-12 m)	2.5	16	10	8
Demersal trawlers (<10 m) & Potters (10-12 m)	5	8	5	4
Demersal trawlers (<10 m) & Potters (10-12 m)	10	4	3	2
Demersal trawlers (<10 m) & Potters (10-12 m)	15	3	2	2
Scallopers (<15 m)	2.5	29	19	15
Scallopers (<15 m)	5	15	10	8
Scallopers (<15 m)	10	8	5	4
Scallopers (<15 m)	15	5	4	3

Table 18. *Calculation of the range on number of trips larger-sized fishing vessels would need to make each day to offset the income from traditional fishing at different prices for kelp.*

Vessel type		Tonnes kelp needed day^{-1} to offset traditional fishing at kelp price £20, £30 or £40 t^{-1} of kelp from Table 31.		
		£20	£30	£40
Potters (>12 m)		105	70	53
Scallopers (>15 m)		161	107	81
	Notional carrying capacity t trip^{-1}	Trips needed day^{-1} to offset traditional fishing at kelp price £20, £30 or £40 t^{1} of kelp		
Potters (>12 m)	2.5	42	28	22
Potters (>12 m)	5	21	14	11
Potters (>12 m)	10	11	7	6
Potters (>12 m)	15	7	5	4
Scallopers (>15 m)	2.5	65	43	33
Scallopers (>15 m)	5	33	22	17
Scallopers (>15 m)	10	17	11	9
Scallopers (>15 m)	15	11	8	6

Table 19. *Results of modelling time required for kelp harvesting and transportation by potters or drift/fixed netters (<10 m) in order to offset their income from traditional fishing at a range of kelp prices and distances between port and the kelp resource. Red shaded cells indicate where the total time required each day exceeds 24 h and is thus impossible to achieve; pink shaded cells indicate where the total time required exceeds 18 h day^{-1} and thus might be difficult to achieve. Heavy boxes indicate viable harvesting envelopes, vessels of this type are unlikely to be able to transport >5 t of kelp each trip so results for last two columns are excluded.*

Kelp price (£t^{-1})	Distance from port to kelp (km)	Total harvest time plus transit time day^{-1} at transport capacity of 2.5, 5, 10 and 15 t in order to make a profit equal to normal fishing activity.			
		2.5	5	10	15
40	5	9.99	6.87	6.58	4.29
40	10	13.24	8.49	7.66	4.83
40	15	16.48	10.11	8.74	5.37
40	20	19.72	11.74	9.82	5.91
40	25	22.97	13.36	10.91	6.45
40	30	26.21	14.98	11.99	6.99
40	35	29.45	16.60	13.07	7.53
40	40	32.70	18.22	14.15	8.07
30	5	13.32	9.16	6.58	8.58
30	10	17.65	11.32	7.66	9.66
30	15	21.97	13.49	8.74	10.74
30	20	26.30	15.65	9.82	11.82
30	25	30.62	17.81	10.91	12.91
30	30	34.95	19.97	11.99	13.99
30	35	39.27	22.14	13.07	15.07
30	40	43.59	24.30	14.15	16.15
20	5	19.99	13.74	9.87	8.58
20	10	26.47	16.99	11.49	9.66
20	15	32.96	20.23	13.11	10.74
20	20	39.45	23.47	14.74	11.82
20	25	45.93	26.72	16.36	12.91
20	30	52.42	29.96	17.98	13.99
20	35	58.91	33.20	19.60	15.07
20	40	65.39	36.45	21.22	16.15

Table 20. *Results of modelling time required for kelp harvesting and transportation by demersal trawlers (<10 m) and potters (10-12 m) in order to offset their income from traditional fishing at a range of kelp prices and distances between port and the kelp resource. Red shaded cells indicate where the total time required each day exceeds 24 h and is thus impossible to achieve; pink shaded cells indicate where the total time required exceeds 18 h day^{-1} and thus might be difficult to achieve. Heavy boxes indicate viable harvesting envelopes, vessels of this type are unlikely to be able to transport >10 t of kelp each trip so results for last column are excluded.*

Kelp price (£t^{-1})	Distance from port to kelp (km)	Total harvest time plus transit time day^{-1} at transport capacity of 2.5, 5, 10 and 15 t in order to make a profit equal to normal fishing activity.			
		2.5	5	10	15
40	5	13.32	9.16	6.58	8.58
40	10	17.65	11.32	7.66	9.66
40	15	21.97	13.49	8.74	10.74
40	20	26.30	15.65	9.82	11.82
40	25	30.62	17.81	10.91	12.91
40	30	34.95	19.97	11.99	13.99
40	35	39.27	22.14	13.07	15.07
40	40	43.59	24.30	14.15	16.15
30	5	16.66	11.45	9.87	8.58
30	10	22.06	14.16	11.49	9.66
30	15	27.47	16.86	13.11	10.74
30	20	32.87	19.56	14.74	11.82
30	25	38.28	22.26	16.36	12.91
30	30	43.68	24.97	17.98	13.99
30	35	49.09	27.67	19.60	15.07
30	40	54.49	30.37	21.22	16.15
20	5	26.65	18.32	13.16	12.87
20	10	35.30	22.65	15.32	14.49
20	15	43.95	26.97	17.49	16.11
20	20	52.59	31.30	19.65	17.74
20	25	61.24	35.62	21.81	19.36
20	30	69.89	39.95	23.97	20.98
20	35	78.54	44.27	26.14	22.60
20	40	87.19	48.59	28.30	24.22

Table 21. *Results of modelling time required for kelp harvesting and transportation by small-medium-sized scallopers (<15 m) in order to offset their income from traditional fishing at a range of kelp prices and distances between port and the kelp resource. Red shaded cells indicate where the total time required each day exceeds 24 h and is thus impossible to achieve; pink shaded cells indicate where the total time required exceeds 18 h day^{-1} and thus might be difficult to achieve. Heavy boxes indicate viable harvesting envelopes, vessels of this type are unlikely to be able to transport >10 t of kelp each trip so results for last column are excluded.*

Kelp price (£t^{-1})	Distance from port to kelp (km)	Total harvest time plus transit time day^{-1} at transport capacity of 2.5, 5, 10 and 15 t in order to make a profit equal to normal fishing activity.			
		2.5	5	10	15
40	5	24.98	18.32	13.16	12.87
40	10	33.09	22.65	15.32	14.49
40	15	41.20	26.97	17.49	16.11
40	20	49.31	31.30	19.65	17.74
40	25	57.42	35.62	21.81	19.36
40	30	65.52	39.95	23.97	20.98
40	35	73.63	44.27	26.14	22.60
40	40	81.74	48.59	28.30	24.22
30	5	31.65	22.91	16.45	17.16
30	10	41.92	28.31	19.16	19.32
30	15	52.19	33.72	21.86	21.49
30	20	62.46	39.12	24.56	23.65
30	25	72.73	44.53	27.26	25.81
30	30	83.00	49.93	29.97	27.97
30	35	93.27	55.34	32.67	30.14
30	40	103.54	60.74	35.37	32.30
20	5	48.30	34.36	26.32	21.45
20	10	63.98	42.47	30.65	24.16
20	15	79.65	50.57	34.97	26.86
20	20	95.33	58.68	39.30	29.56
20	25	111.00	66.79	43.62	32.26
20	30	126.68	74.90	47.95	34.97
20	35	142.35	83.01	52.27	37.67
20	40	158.03	91.11	56.59	40.37

Table 22. *Results of modelling time required for kelp harvesting and transportation by larger potting vessels (>12 m) in order to offset their income from traditional fishing at a range of kelp prices and distances between port and the kelp resource. Red shaded cells indicate where the total time required each day exceeds 24 h and is thus impossible to achieve; pink shaded cells indicate where the total time required exceeds 18 h day^{-1} and thus might be difficult to achieve. Heavy boxes indicate viable harvesting envelopes, vessels of this type are unlikely to be able to transport >10 t of kelp each trip so results for last column are excluded.*

Kelp price (£t^{-1})	Distance from port to kelp (km)	Total harvest time plus transit time day^{-1} at transport capacity of 2.5, 5, 10 and 15 t in order to make a profit equal to normal fishing activity.			
		2.5	5	10	15
40	5	36.64	25.20	19.74	17.16
40	10	48.53	31.14	22.99	19.32
40	15	60.43	37.09	26.23	21.49
40	20	72.32	43.03	29.47	23.65
40	25	84.21	48.98	32.72	25.81
40	30	96.10	54.93	35.96	27.97
40	35	107.99	60.87	39.20	30.14
40	40	119.89	66.82	42.45	32.30
30	5	46.64	32.07	23.03	21.45
30	10	61.77	39.64	26.82	24.16
30	15	76.91	47.20	30.60	26.86
30	20	92.04	54.77	34.39	29.56
30	25	107.18	62.34	38.17	32.26
30	30	122.31	69.91	41.95	34.97
30	35	137.45	77.47	45.74	37.67
30	40	152.58	85.04	49.52	40.37
20	5	69.95	48.10	36.20	30.03
20	10	92.66	59.45	42.14	33.82
20	15	115.36	70.80	48.09	37.60
20	20	138.06	82.16	54.03	41.39
20	25	160.76	93.51	59.98	45.17
20	30	183.47	104.86	65.93	48.95
20	35	206.17	116.21	71.87	52.74
20	40	228.87	127.56	77.82	56.52

Table 23. *Results of modelling time required for kelp harvesting and transportation by larger scallopers (>15 m) in order to offset their income from traditional fishing at a range of kelp prices and distances between port and the kelp resource. Red shaded cells indicate where the total time required each day exceeds 24 h and is thus impossible to achieve; pink shaded cells indicate where the total time required exceeds 18 h day*$^{-1}$ *and thus might be difficult to achieve. Heavy boxes indicate viable harvesting envelopes, vessels of this type are unlikely to be able to transport >10 t of kelp each trip so results for last column are excluded.*

Kelp price (£t^{-1})	Distance from port to kelp (km)	Total harvest time plus transit time day^{-1} at transport capacity of 2.5, 5, 10 and 15 t in order to make a profit equal to normal fishing activity.			
		2.5	5	10	15
40	5	54.96	38.94	29.61	25.74
40	10	72.80	48.13	34.48	28.99
40	15	90.64	57.32	39.34	32.23
40	20	108.48	66.51	44.21	35.47
40	25	126.31	75.70	49.07	38.72
40	30	144.15	84.89	53.94	41.96
40	35	161.99	94.07	58.80	45.20
40	40	179.83	103.26	63.67	48.45
30	5	71.62	50.39	36.20	34.32
30	10	94.86	62.28	42.14	38.65
30	15	118.10	74.18	48.09	42.97
30	20	141.35	86.07	54.03	47.30
30	25	164.59	97.96	59.98	51.62
30	30	187.83	109.85	65.93	55.95
30	35	211.08	121.74	71.87	60.27
30	40	234.32	133.64	77.82	64.59
20	5	108.26	75.59	55.94	47.20
20	10	143.40	93.43	65.13	53.14
20	15	178.53	111.26	74.32	59.09
20	20	213.67	129.10	83.51	65.03
20	25	248.80	146.94	92.70	70.98
20	30	283.94	164.78	101.89	76.93
20	35	319.07	182.61	111.07	82.87
20	40	354.21	200.45	120.26	88.82

6.3 Potential for Kelp Harvesting as a Diversification Opportunity for Scottish Fishers

KEY POINTS

- **Economic analysis suggests that seaweed harvesting would probably not be a financially attractive diversification option for the majority of Scottish fishing vessels**
- **Seaweed harvesting could provide some other opportunities for inshore fishers, for example conducting monitoring surveys**

The economic feasibility of harvesting mechanically seaweeds was examined based on the harvesting practices for *L. digitata* and *L. hyperborea* in France, and for *L. hyperborea* in Norway, but applied to fishing vessels operating in the West of Scotland. The basic principle adopted is that the quantity of kelp that must be collected needs to compensate for the forgone income from traditional catches. On this basis the financial analysis explored profit sensitivity to factors such as price variability of harvested seaweed, type of boat, and collection model used. Two concepts were explored: (1) a single licence-holder model with management responsibility requiring more fully integrated operations; (2) licensing of workboat operators. In both cases profitability of collecting kelp is reported.

In France the turnover from harvesting 40,000-60,000 t y^{-1} (wet weight) of *Laminaria digitata* is £1.7-2.7 million (assessed from Mesnildrey *et al.* (2012) converting Euros to 2012 GBP after correcting for inflation by consumer price index). The average price of this product is estimated at £35-38 t^{1}.

The kelp are harvested mainly by fishing vessels which are converted for part of the year to deploy the ‘Scoubidou’ (Figure 31). The typical vessels involved are scallop dredgers where the scallop dredge is normally deployed from the stern. This is an important point as the design of typical scallop dredgers operating around Scotland is different.

Figure 31. *Typical Scoubidou vessel operating in Brittany, France (source: Mesnildrey* et al., *2012*)

Around 60 of these type of vessels collect kelp in the near shore waters for around 100 days y^{-1} during the spring and summer seasons. The average annual production per vessel is 1,200 t based on 12 t day^{-1}. Vessels are limited to a single trip each day so this capacity must be carried on the vessel. Typically the vessels are around 10 metres long with a GRT of 10-12 and an engine power of 70-80 kW (Alban *et al*., 2011). Importantly there have been changes in the fleet structure with the exit of some smaller vessels resulting in decrease in fishing effort but increase in catch-per-unit-effort over time. The capital cost of a vessel now is nearly £150,000 (Frangoudes, K., 2017, personal communication).

The economics of a fishing vessel in the Iroise Sea (Brittany) based on 2008 data showed an average turnover of £108k, of which nearly 50% came from seaweed harvesting and the remaining from scallop dredging (Table 24)

Operating costs were £83k (nearly £830 per day) giving a gross operating profit of £25k, equal to 24% of the gross revenue (Alban *et al*., 2011). The quantity harvested by each vessel in 2008 was a little higher than at present at around 1,400 t or around 14 t day^{-1}. From the analysis of the vessel costs the average harvest cost can be estimated at £32 t^{-1} with the local alginate industry paying £38 t^{-1} for raw material. The price is decided by agreements between the industry and the fishermen at the beginning of each year and has not shown substantial fluctuation over the last 15 years (Frangoudes, K, 2017, personal communication).

Table 24. *Economics of a typical French vessel harvesting* L. digitata *based on data from Alban* et al. *(2011). All values converted from Euros to £sterling (in 2012 GBP Pounds, after removing inflation).*

Turnover (£y^{-1})	108,620
Total cost (£y^{-1})	83,062
Gross operating profit (24% of the turnover) £y^{-1}	25,558
Turnover from Kelp (55% of total turnover) £y^{-1}	59,751
Days harvesting kelp (y^{-1})	100
Average income from kelp (£day^{-1})	597
Average operating cost (£day^{-1}) while harvesting kelp (assumed at 75% of the average income from kelp)	450
Harvest (t day^{-1})	14
Average cost of harvest (£t^{-1} day^{-1})	32

Harvesting of kelp in Norway follows a different model to France in that a fleet of dedicated vessels is used (Figure 32).

Figure 32*. The Norwegian kelp harvesting vessel owned FMC Biopolymer. From (Vea & Ask ,2011)*

Norwegian seaweed harvesting vessel characteristics are shown in Table 25. There is no information in the literature about the operating costs of these vessels but it is reasonable to assume between 80-90% of gross income may be applicable based on figures deduced for French and UK fishing vessels.

Table 25. *Economics of a typical Norwegian vessel harvesting* L. hyperborea *(some data available from Harald Bredahl, FMC Biopolymer, 2017, personal communication; others indicated with (*) are our assumptions)*

Length (m)	Power (KW)	Capacity (t)	Operational days y^{-1}	Number crew	Capital cost (£m)	Price paid for seaweeds (£)	Revenue/day (£)	Harvest rate (t d^{-1})	(*) Average cost of harvest d^{-1} - assumed at 85% of the revenue (£)	Cost of harvest (£t^{-1})
13-17	227-378	60-120	150-250	2	3-4	19	1,697	90	1,442	15-16

According to FAO statistics 1,400 tonnes of ‘dry seaweeds and other algae unfit for human consumption’ were imported into the UK in 2013, with a total value of nearly $4.2m (FAO, 2016). This is equivalent to £2,480 t^{-1} dry wt or £248 t^{-1} wet wt, assuming a 10:1 wet to dry weight conversion. This raw material cost is 6.5 times higher than the cost of the raw materials harvested by the French model, or 15 times higher than the Norwegian one. However, direct comparison is difficult because the FAO data do not discriminate seaweed by species, and although the category implies use for agriculture or industrial processing, the figure might include some high-value materials. Import costs are available for some other countries e.g. the cost of seaweed imported into France was nearly £930 t^{-1} dry wt in 2012 (FranceAgriMer, 2011). The latter value can be considered a reliable figure of the import price of seaweed into Europe and is still much higher (at least double) than the marginal cost of local production. The main message here is that importing seaweed for processing appears to be much more expensive than harvesting it locally.

Based on the FAO data, and assuming a 10:1 wet to dry weight conversion, nearly 14,000 t wet wt of seaweed were used by the UK industry in 2013. This means that there is at least a minimal internal demand that could be satisfied by harvesting local resources that if treated for the extraction of alginate and agar would generate products of higher added value from 4 (fresh alginate) to 10 (fresh agar) times more valuable than the raw materials, according to the import value of these products in the French market (FranceAgriMer, 2011).

6.4 Economic Feasibility of Harvesting Seaweeds Using UK Fishing Fleet Vessels

The main kelp resources are located in Scottish waters, so diversification opportunities would mainly apply to the Scottish inshore fleet although vessels from further afield might be attracted if profit margins were sufficiently high.

To assess the diversification potential of kelp harvesting for fishing vessels the following elements were considered:

1. The types of fishing vessels in the Scottish fleet;
2. The hold volume and loading capacity of fishing vessel that do not alter the stability of the vessels;
3. The selling price of the raw material;
4. The average operating costs of harvesting, and
5. The total volume that can be absorbed by the market.

The composition of the Scottish fleet is shown in (Table 26). The ten metre and under fleet is dominated by vessels using baited creels, traps or baskets to catch shellfish. In 2015, 88 per cent of the ten- and under ten-metre vessels were engaged in creel fishing. Of the 566 over ten metre vessels, 64 per cent were fishing mainly for shellfish and 32 per cent were demersal. Creel fishing vessels and *Nephrops* trawlers dominate the over ten metre shellfish group, whilst trawlers dominate the demersal group. The large over 40 m vessels are pelagic trawlers plus two purse seiners. Pelagic vessels are specialised and would not be suitable for conversion to kelp harvesting so can be discounted from consideration.

Table 26. *The Scottish fishing fleet in 2015 (Marine Scotland, 2016b).*

Length (m)	Number	Number (%)	Average tonnage (GRT)	Average power (kW)
< 10 m	1,449	72	4	55
>10-12	145	7	13	136
>12-15	69	3	22	183
>15-24	232	12	111	326
>24-40	94	5	273	639
>40	26	1	1,650	4,120
Total	2,015			

The majority of fishing vessels which might be located close to the kelp harvest areas will thus be from the ten-metre and under sector with some larger trawlers (Figure 33). Many of these smaller vessels are engaged in trawling for *Nephrops*, the newer vessels have covered sorting decks but some older open vessels are still in operation. The catch is dropped through a hatch into the sorting deck, usually via some sort of hopper or pound. The sorted prawns are then put on ice and placed in the hold usually in large plastic trays.

Figure 33. Nephrops *trawl fishing vessels typical of the inshore west coast fleet, Oban harbour (© C Fox, SAMS).*

Potting vessels are often very small and may be operated by a single person (Figure 34). Modern designs are often based on catamaran because the emphasis is on getting to the fishing grounds quickly and returning the catch fresh to the landing port. There are also a number of larger potting vessels in the fleet, sometimes called ‘super-crabbers’.

Figure 34. *Small crab potter that can be operated by one or two people (source: https://www.findafishingboat.com/kingfisher-24-potter-netter/ad-88986)*

The intermediate size category >12-40 m also includes vessels engaged in scallop dredging (Figure 35). These vessels normally deploy sets of dredges from either side of the vessel. These vessels tend to have larger open decks because recovery of the dredges would be hampered by closed weather-deck shelters.

Figure 35. *Scallop dredger in Oban harbour (© C Fox, SAMS)*

There are a large range of vessel designs operating around the Scottish west coast so in order to estimate potential kelp carrying capacity we examined a range of typical designs built by Macduff Ship Design Limited[1] who provided the blueprints of the vessels considered in the Figure 36. From these drawings the hold volumes were estimated (Table 27).

Based on the design blueprints the 8 m potter/fisher design could carry no more than 4 t of kelp; the 9.95 m vessel up to 5 t and up to 15 t by the 14.95 m scalloper (Table 27). However, vessel stability must also be taken into account in addition to hold capacity and for this reason Macduffs would not recommend more than 2 t be loaded for the smaller vessel design.

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[1] http://www.macduffshipdesign.com/index-2.html

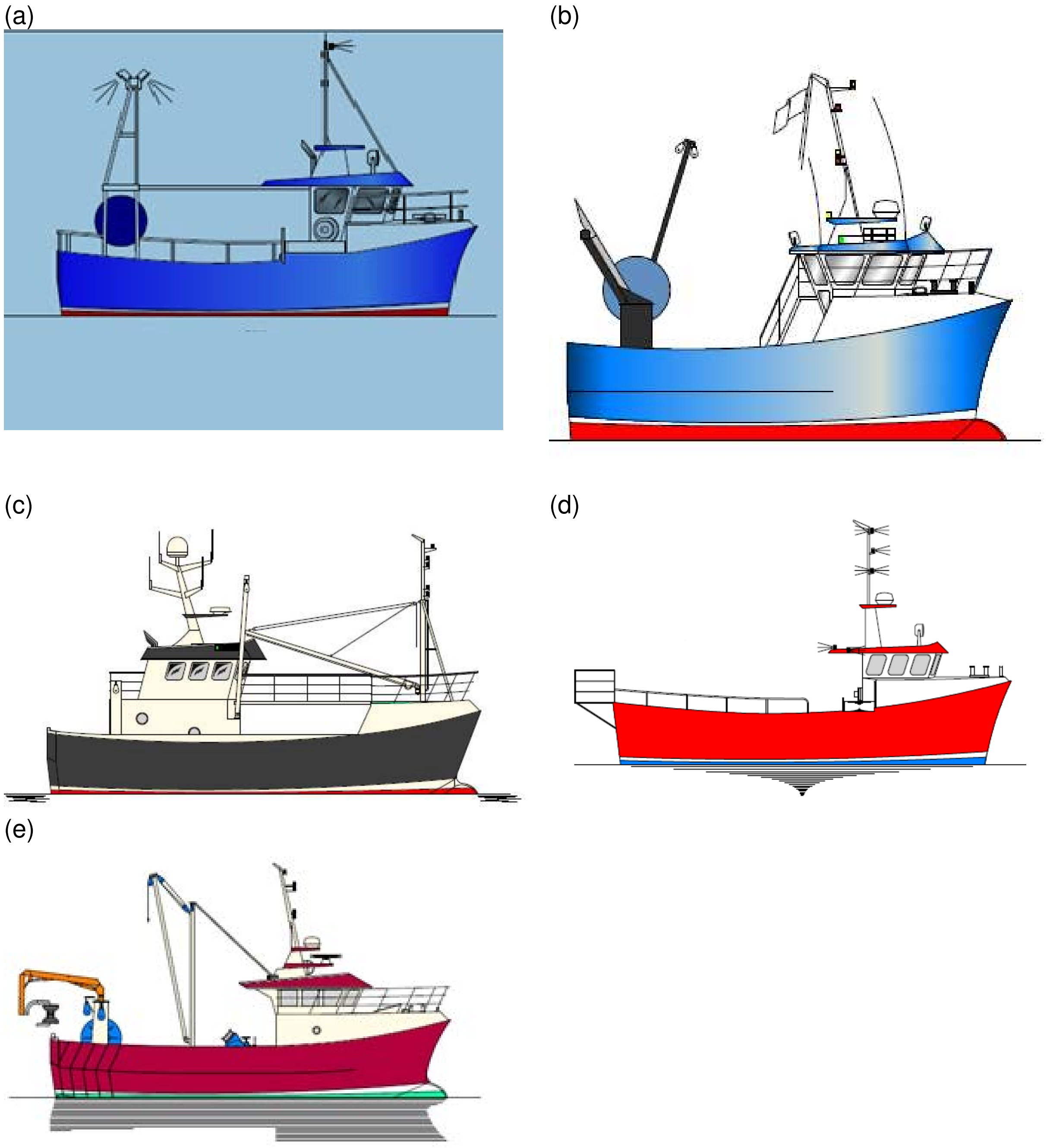

Figure 36. *Inshore fishing vessel designs by Macduff Shipyards (a) 8 m general purpose general purpose trawler which can be adapted for potting (b) 9.95 m general purpose trawler (c) 14.95 m scalloper (d) 10 m crabber (e) 14.95 m general purpose trawler/scalloper*

__Table 27__. Hold volume and capacity of inshore fishing vessel designs based on Macduff Shipbuilders blueprints

Vessel type	Hold volume (m^3)	Potential kelp capacity (t) assuming 0.5 t m^3	Capacity recommended by McDuffs (t)
8 m Fisher/Potter	8	4	2
9.95 m Fisher/Crabber	7	3.5	4-5
9.95 m Trawler	7.5	4	7
14.95 m Trawler/Scalloper	27	13	13-15

Comparing the length and engine characteristics of the fishing vessels used in France to collect kelp with the composition of the Scottish fishing fleet, one can see that only 10% of Scottish vessels are of equivalent length and engine capacity (Table 26). Smaller vessels in the ten-meter and under group would be unlikely to have either the carrying capacity or stability if fitted with cranes similar to those used in France. However, smaller catamaran designs might fulfil the twin objectives of capacity and stability but this could not be evaluated fully without further work with naval architects. The calculated holding capacities of Scottish design 10 m vessels (Table 27) are actually lower than those reported for the scallopers used to collect kelp in Brittany, France. This may be because the French vessel designed for both scallops dredging and seaweeds harvesting tend to be beamier and thus may have more open deck on which kelp also appears to be stowed for transport (Figure 37). When fishing for scallops the French vessels deploy the scallop dredges from the stern in contrast to typical Scottish operations where the dredges are deployed from either side of the vessel. Only the larger Scottish design trawler/scalloper could carry more kelp.

Figure 37. *French fishing vessel transporting kelp to harbour (© Julie Maguire, Indigo Rock Marine Research Station)*

To assess the economic potential of using Scottish fishing vessels for harvesting kelp it was assumed that the price of kelp in the UK internal market could be somewhere between current estimated Norwegian price (£20 t^{-1} wet wt.) and the French price (£40 t^{-1} wet wt.).

As regards the costs of harvesting, it was assumed that these would be close to the costs of operating the different classes of fishing vessel. For some categories of fishing vessels that can be suitable for harvesting different costs lines (operating costs) in 2012 constant GBP are reported in the Table 28 along with the income generated.

Discussion with the Maritime and Coastguard Agency (MCA) confirmed that changing a vessel activity from normal fishing to kelp harvesting would require a re-certification of the vessel as a workboat (MIN 514 M, 2017).This would involve a vessel inspection by a third-party auditor and an additional fix costs estimated at £2,000 every 5 years plus an additional £250 for annual inspections. This however excludes the costs of any vessel modifications required. Such modifications might be quite limited for the medium-sized vessels, which would normally already be fitted with a crane (trawlers, scallopers). However, potters usually have a different creel-lifter which is located around deck level and would not be suited to lifting loads of kelp onto the vessel. No vessel would be allowed to operate in Scottish waters without an MCA licence, which has implications for bringing over any vessels from other countries that do not adhere to MCA coding requirements.

Table 28. *Income and operational costs of UK inshore fishing vessels. Data are taken from the Seafish fleet economic performance dataset 2006-2016 which covers the whole of the UK. The figures reported are the average of the last 10 years deflated by consumer price index in constant 2012 GBP. http://www.seafish.org/research-economics/industry-economics/seafish-fleet-economic-performance-data*

Vessel type	**Income** (£d^{-1})	**Fuel** (£d^{-1})	**Crew** (£d^{-1})	**Other costs** (£d^{-1})	**Vessel cost** (£d^{-1})	**Total** (£d^{-1})
Demersal trawlers <10 m	747	101	198	114	185	598
Drift/fixed netters <10m	550	54	147	74	107	383
Potters <10m	512	70	146	70	105	391
Potters 10-12m	778	72	232	131	142	577
UK scallop dredgers <15 m	1,407	256	381	179	341	1,157
French scallop dredgers (55% of income is coming from seaweeds)	1,086					450

The feasibility of economically adapting fishing vessels to kelp harvesting depends on the potential loads certified by the Maritime and Coastal Agency and the average selling price of kelp. It is assumed that the carrying capacity of the vessels is the limiting factor and that sufficient harvestable biomass is available as examined in Chapter 2 of this report.

It was assumed that the safe loads for various vessel designs are those suggested by McDuff shipbuilders (Table 27). By assuming an interval price for fresh kelp of £20-40 t^{-1} wet wt. it is evident that at least 10 t d^{-1} must be collected at the highest price for small potting vessels to cover their operating costs, while a daily harvest of 12-30 t is needed for the 10-12 m vessels. Even higher daily harvests are required for a 15 m scalloper at 29-58 t because of the higher running costs of these vessels (Table 29). These figures raise relevantly when assuming a minimum price of £20 per tonne that would make the use of local vessels economically unfeasible to break even. Considering that the stable load for the typologies of vessels reported in the Table 27 is lower than 10 tonnes with the exception of the 15 m trawler/scalloper, harvesting by traditional fishing vessels would be economically feasible only if at least 2 operations of loading and unloading were possible in a day. This implies that the area of harvesting must be close to the home port.

Table 29. *Harvest needed to break even the total cost of fishing. All values rounded to nearest tonne.*

Vessel type	Kelp price scenarios ($£t^{-1}$)			Total cost per day (£)
	20	***30***	***40***	
Demersal trawlers <10 m	30	20	15	598
Drift/fixed netters <10 m	19	13	10	383
Potters <10 m	20	13	10	391
Potters 10-12 m	29	19	14	577
UK scallop dredgers < 15 m	58	40	29	1,157
French scallop dredgers	22	15	11	450

While Table 29 describes the quantity of kelp which would need to be harvested by each vessel type to cover their typical operating costs, the opportunity costs (income) from fishing are higher than the operating costs (else no vessels would make any profit). Based on Seafish Economic Survey data, daily incomes from fishing range from just over £500 for a small potter to nearly £800 for a larger potter. Scallop dredging opportunity costs are around £1,400 d^{-1}. Based on these figures at least 13-20 t of kelp would need to be harvested by small non-scalloping vessels at the highest price of £40 t^{-1} wet wt. For an under 15 m scalloper the offset harvest rises to 29 t d^{-1} (Table 30). If kelp purchase prices were as low as £20 t^{-1} then the minimum offset harvests range from 26-71 t day^{-1}.

Comparing the minimum offset harvests (Table 30) with estimated carrying capacity of vessels in the inshore fleet raises an obvious problem. Even the <15 m scalloper could only transport about 50% of the kelp needed for it to achieve the daily offset at the highest kelp price. All the vessel types would need to make at least 2-3 collecting trips each day, at lower prices 3-6 daily trips would be needed. This implies that the kelp resource would need to be very close to the off-loading destination for this to be a practical proposition.

Table 30. *Opportunity cost (income) from traditional fishing activities for different vessel types plus the offset harvest quantities of kelp (rounded up to the nearest tonne) which would need to be collected each day at a range of kelp price intervals.*

Vessel type	Traditional activity income ($£d^{-1}$)	Kelp price scenarios ($£t^{-1}$ wet wt.)		
		20	***30***	***40***
Demersal trawlers <10 m	747	38	25	19
Drift/fixed netters <10 m	550	28	19	14
Potters <10 m	512	26	18	13
Potters 10-12 m	778	39	26	20
Scallop dredgers < 15 m	1,407	71	47	36
French scallop dredging vessels (income only from kelp)	597	30	20	15

Two additional categories of vessels greater than 10 metres could potentially have the technical suitability for harvesting kelp. These categories were selected based on the average length, gross registered tonnage and engine power specifications that resemble those of the dedicated Norwegian kelp harvesting vessels (Table 25). The opportunity costs for these vessels (Table 31) are higher than for the small inshore vessels considered above (Table 30) so they would require higher harvest rates each day that could be only feasible if at least 2 trips from the home port to the closest harvesting area were carried out in a day at the selling price of seaweeds higher than £30 per tonne (this estimate is based on the assumption that no more than 15 tonnes can be arranged in the hold).

Table 31. *Opportunity cost (income) from traditional fishing activities for larger vessel types plus the offset harvest quantities of kelp (rounded up to the nearest tonne) which would need to be collected each day at a range of kelp price intervals.*

Vessel type	Traditional activity income (£d^{-1})	Kelp price scenarios (£t^{-1} wet wt.)		
		20	***30***	***40***
UK Potters > 12 m	2,094	105	70	53
UK Scallop dredgers >15 m	3,206	161	107	81

The vessels in Table 31 show opportunity costs that are higher than those reported for the bespoke Norwegian harvesting vessels (Table 25), therefore it is evident how even at kelp prices higher than £30 t^{-1} wet wt the quantity of seaweeds that needs to be collected daily becomes very large for kelp gathering to be more profitable than normal fishing activity.

The total number of fishing vessels in the Scottish fleet which would be available to collect the necessary quantity of raw material required presently by the UK hydrocolloids industry appears limited. From the UK fishing vessel list, it is possible to find 17 vessels in the West of Scotland and Islands <10 m that have specifications close to the French vessel (in terms of GRT and length), and therefore adaptable to be used as harvester. If they collected each 10 to 15 t d^{-1} in 100 days, this would generate a total production of 17,000 to 25,500 t y^{-1}.

Looking at other vessels from 10-12 m with a GRT: Length ratio between 1.3 and 1.5 it is possible to find from the dataset 22 suitable vessels in the port of Ayr, Campbeltown, Kirkwall, Lochinver, Oban, Scarborough, Stornoway, Portree and Ullapool. At the rate of 12 t d^{-1} and operating timescale of 100 days per year, it is possible to collect 26,000 tonnes (see section on Modelling seaweeds harvesting with local fishing vessels).

The adoption of a bigger vessel such as the scallop dredger (<15 m) suitable for harvesting *L. hyperborea*, would allow a gathering up to 30 t d^{-1}; a small fleet of 10 vessels would harvest a total amount of 30,000 tonnes in a season (100 days). From the research market carried out by AB-SIG (2013) it is evident that an amount of kelp in the range t 20,000 to t 30,000 would be suitable for the internal (UK) market and would not generate price distortion (i.e. a drop in the price due to excess of supply) in an industry that appears at saturation AB-SIG (2013).

The above analysis suggests that the only vessels in the Scottish fleet where conversion to kelp harvesting might be economically feasible would be those between 10-15 m but these only comprise about 10% of the Scottish fleet. Within this group many vessels would not be suitable for conversion due to their limited hold-space or covered deck areas. To be economically attractive vessels would need to make multiple harvesting trips each day implying that the kelp resource would need to be very close to the landing locations.

Alternative scenarios are possible. For example, a larger barge could be used to transport material with smaller fishing vessels supplying the barge. This could prove economically cheaper, at least in the short-term, than investing in a fleet of dedicated harvesting and transporting vessels, as used in Norway. However, examining the economics of this scenario is beyond the scope of the present report.

6.4.1.1 Alternative opportunities for fishermen

The focus of the economic feasibility assessments have been based on looking at the use of fishing boats for kelp harvesting activities. It should be noted that there may be alternative ways in which fishermen can participate in a kelp harvesting industry without undertaking the actual harvesting activities. For example, the local knowledge of fishermen would be sought to help devise sampling programmes. Fishing vessels could be used as platforms from which to undertake survey activities, which would large scale time investments and a need to shift away from primary fishing activities. These opportunities are hard to place economic figures on as they are small scale and part-time in nature. However, discussions between developers and local fishermen may reveal potential collaborations that could benefit both parties, and should be explored during stakeholder consultation.

6.4.2 Modelling seaweed harvesting with local fishing vessels

The following section presents two different models for seaweed gathering to assess the range of average costs of harvesting. In the first model, it is assumed that small vessels (<10 m) will be used, operating with two scoubidou for the collection of *L. digitata*, while in the second a medium size (10-12 m) modified trawler/scalloper is used, arranged with a rake for the collection of *L hyperborea*. The figures proposed are working on a day basis and consider the main variable factors (crew, fuels, vessel costs and cost of reclassifying a fishing vessel to a workboat). Fixed costs are not included here, but in the discount cash flow and profitability analysis (Section 6.4.3); shipping is considered to provide an idea of the order of magnitude of the cost of shipping fresh product to important processors based in Scotland and Norway.

6.4.2.1 Modelling of Laminaria digitata *harvesting*

The first model is based on the collection of *Laminaria digitata* using the scoubidou technology adopted by the French scalloper, installed on typical small vessels available in the West of Scotland (small potters/ craber/ trawlers). It has been assumed that harvesting will happen in the Outer Hebrides and along the coastline of the Highlands. The main ports considered for logistic operations are those having a fleet suitable for harvesting and closest to kelp beds (Ullapool, Stornoway, Oban; Table 12). At the initial stage of this business, it has been considered to use no more than 12 vessels to give the industry the possibility to cope with a small production and avoid the saturation of the market.

A second model based on a workboat such as the bespoke Norwegian seaweed trawler to transport the harvest to the port of Haugesund (Norway-436 nm from Stornoway) to be processed by FMC Health and Nutrition or to the port of Ayr (424 nm from Stornoway) to be processed by MBL (Marine Biopolymer), and simulate in this case the absence of any source of kelp harvested close to the processing industry.

It has been assumed that a medium vessel of 10-12 m with 2 “scoubidou” can safely hold (i.e. without losing stability) 6 tonnes of load. Assuming the operational areas are not far more than 5-10 km from the home port, it would be possible to harvest twice a day and thus collect an ideal total of 12 tonnes per day. Therefore, the total kelp harvestable in a single day by 12 vessels is assumed to be 144 tonnes.

The operating costs for small/medium vessels (according to Table 28) is estimated in £400 to £800 d^{-1} [2], respectively. The total cost of collecting 144 tonnes of kelp per day is estimated at £4,800-£9,600 d^{-1}, equivalent to £33-£66 t^{-1}.

Shipping kelp to the port of Haugesund or Ayr can take two days of navigation (at the average speed of 10 knots). The estimated number of days at sea is four, including the return trip. The average operating cost is estimated at £3,400[3]. Adding the cost of transport, the full cost of delivering 144 t to the above mentioned ports is £8,200-£13,000. The average cost per tonne of seaweed is then estimated at £58-91, while the cost of transport can be assumed to be £24 per tonne.

The above figures show a marginal cost of harvesting compatible with the French scalloper. It seems implausible using the local fishing fleet to harvest at a cost lower than £33 t^{-1}, but this marginal cost would be sufficiently high to start a negotiation between the harvesters and the UK hydrocolloids industry at price of £40 t^{-1} wwt or even a bit higher, if the processing plant were located close to harvesting areas. However, at the highest marginal cost of £91 t^{-1} wwt harvesting could be still feasible if shipped at a distance of 400nm, being the latter price of the same order of magnitude (£93 t^{-1} wwt) of the French market import price.

6.4.2.2 Modelling of Laminaria hyperborea *harvesting*

For the collection of *L. hyperborea* we consider a modified trawler/scalloper <15 metres with an open hold able to accommodate a maximum load of 15 tonnes. We are assuming that it operates dragging a rake that collects at each operation at least 1,000 kg of seaweeds. If this collection is achieved every 15 minutes, in 1hr it is possible to harvest 4 t and fill in the hold in ½ working day. In a day it is possible to collect at most 30 tonnes if we assume that the harvesting operations are carried out in a plot closer to the home port. Simulating the presence of five vessels, the total load per day could be 150 tonnes (and 15,000 per year). This could be transported to destination using as a workboat the Norwegian vessel already introduced for the transport of *L. digitata*. At the operating cost per day of nearly £1,200 (see the Table 28), the unit cost of harvesting seaweeds would be £40 t^{-1} and the cost of transport can be assumed equal to £24 per tonne as modelled for *L. digitata*.

6.4.3 Modelling a transferable quota system

In this section we use the cost of harvesting modelled for the local fishing vessels to propose a simple plan for distributing efficiently quotas of harvesting under a cap and trade system. Aim is to show how vessels having different marginal costs might operate to minimise cost of production, and not to describe mechanisms and costs of implementing a cap and trade system. We introduce a cap to assure the maximum amount of kelp harvestable, while the trade guarantees the efficient distribution of resources between producers. If we make the assumption of a quadratic cost function (this assumption is not yet supported by the

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[2] This is the cost per day of a small medium vessel 10 metre long reported in the Table 27 considering only 1 crew and removing the line of cost named “other costs of fishing”.

[3] We are assuming that the highest operating costs are deduced by the following figures: two crew members at £150 d^{-1} each, fuel 350 d^{-1}, other vessel costs: £200 d^{-1}.

evidence because of the absence of any mechanised harvesting industry), the marginal cost of production can be considered linear as shown in the Figure 38, and equal to the average costs of production assessed in the Section 6.3.

According to the criterion of economic efficiency, the number of quotas should be distributed between vessels in a way that different fisheries face the same marginal costs of production. Starting from an equal distribution of quotas between the two vessels (15 quotas each), as shown at point X in the Figure 38, it is evident that if there is in place a mechanism for transferring quotas, the vessel with the lowest marginal cost (MC1) buys quotas from the second vessel (MC2). This transfer happens until the quota exchange reaches the point B where the marginal cost of production for the two vessels is the same.

Let us assume that there are two fishing vessels operating one at the marginal cost of £30 t^{-1} and the second at the cost of £40 t^{-1}, when the average daily harvest is 15 t d^{-1}, and that the marginal revenue (unit kelp price) is £36 t^{-1}. We can assume that the marginal cost is changing linearly around the average level of harvesting. We consider also that the maximum number of quotas is 30, and each quota correspond to 1 tonne of harvest per day. It is appealing to distribute quotas in an equitable way, i.e. 15 quotas to each producer (point X). At point X the cost of harvesting 15 quotas for the vessel 1 is £450, while the cost of harvesting for the vessel 2 is £600. The total cost for the two producers under “equitable” share of quotas is £1,450. However, the two businesses have the same cost of production (£520) only when producer 1 shares 17 quotas and the second producer 13 quotas as shown in Figure 38 at point B (in this figure we read the MC1 for the harvester 1 from left to right and the MC2 for harvester 2 from right to left along the x axis). The total cost of the joint production is in this case £1,040, and is the lowest possible to make the two producers maximising their profits (for both the marginal costs at point B is equal to the marginal revenue, the value of 1 quota of harvest). This marginal cost at the equilibrium (point B) is nearly £35 t^{-1} and this must be the optimal price of 1 quota of harvest. If the prices of kelp was lower than £35 t^{-1} not all the 30 quotas would be exchanged on the market (else excess of supply), while at prices higher than £35 t^{-1} there would be an excess of demand with a higher request of quotas to the regulator.

In order to have an effective negotiation at the starting point X, the value of the quota should be higher than the marginal operating cost of the most efficient harvester, but lower than the marginal (least efficient) producer. In other terms, for the example provided here the marginal revenue should be bounded between £30 and £40 per tonne. At prices lower than £30 t^{-1} there would not be t any negotiation because the value of the quota is lower than the cost of production and both the producers have an incentive to sell quotas. At prices higher than £40 t^{-1} both producers would have an incentive to buy, therefore even in this case there is not any room for negotiation. At intermediate values, harvester 2 has incentive to sell 2 quotas to harvester 1. At the equilibrium, the two producers face the same marginal cost of production that is equal to the marginal revenue, the value of the quota. So at the equilibrium the system is distributing 30 quotas, 17 to the producer 1 and 13 to the producer 2.

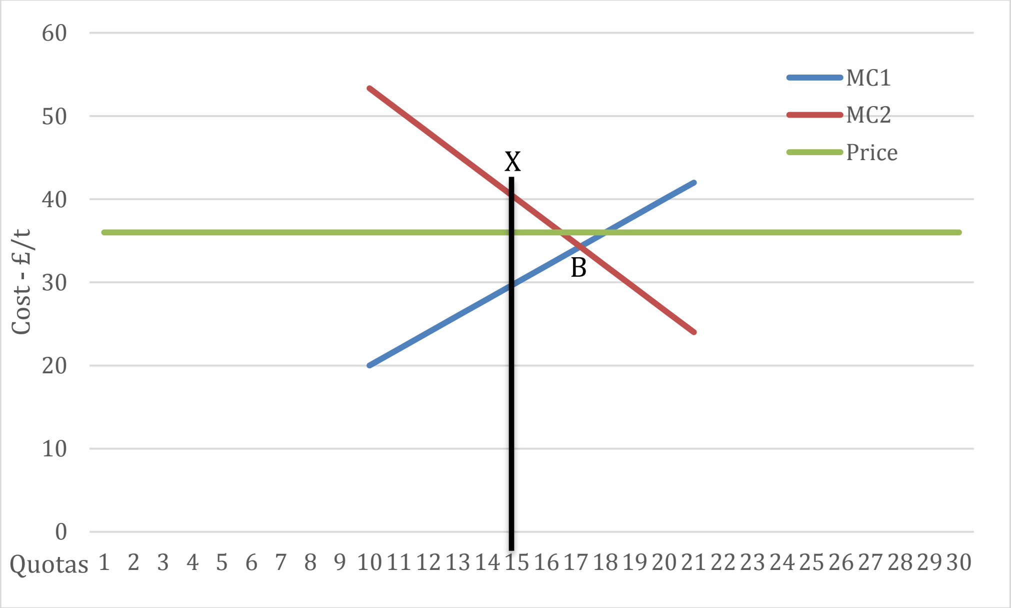

Figure 38. *A quota system for two producers sharing 30 quotas*

6.4.4 Analysis of discounted cash flow

The scope of the economic feasibility and modelling is based on consultation with planners, business operators and potential business operators. There is a small number of relevant stakeholders in the private sector from which to draw empirical data, so representative values have been used in conjunction with better empirical data from other countries, including France and Norway.

The ownership structure within an operational model for large scale harvesting will depend on the licencing arrangements: (1) a single licence-holder model with management responsibility, requiring fully integrated operations; and (2) a scenario of licensing workboat operators in a similar manner to fishing fleets.

The starting assumption has been that *Laminaria* seaweed harvesting should be competitive against international harvesting comparators. This involves an assessment of costs and seaweed prices which would determine the economic viability of *seaweed harvesting only.*

In this section we provide some economic scenarios of seaweed harvesting and related financial indicators commonly used under a discounted cash flow (DCF). We do not include in the DCF costs of monitoring, and revenues and costs from kelp processing because of lack of reliable information, but we focus only on the process of harvesting. We consider that harvesting can be managed by two different ownership structures: (1) a single licence-holder model; and (2) licensing of workboat operators in a similar manner to fishing fleets.

6.4.4.1 The single licence model

Under the single licence holder model, we propose two different concepts (the French vessel, and the Norwegian trawler) to work out what the most profitable approach is. For both concepts we consider that the lifespan of the investment is 30 years and the discount rate is set at the level of 3.5%, a value that can be assumed a lower bound return of alternative projects in the primary sector. Price for kelp is assumed to range from a minimum of £30 t^{-1} to a maximum of £40 t^{-1}. Prices under £30 t^{-1} are not economically feasible, but a small mark-up applied to kelp price of £40 t^{-1} is considered to simulate the effect on profitability of a higher quality product. The average variable cost of harvesting is assumed to be £500 d^{-1} for the first concept and £1,500 d^{-1} for the second. The fix costs for the French typology vessel is assumed to be £3,750 y^{-1} as a reasonable depreciation cost of a capital asset that is worth £150,000. Conversely, the big Norwegian trawler is assumed to have a high fixed cost of £75,000 y^{-1} being the capital value of a new trawler equal to £3,000,000. An additional fix cost of £650 y^{-1} is introduced to take into account classification as a workboat and inspection as suggested by the certifying authorities. Under the first concept, we provide two scenarios: one based on a limited number of vessels (three vessels since time zero and an addition of three vessels since the year fourth) to take into account that a small local industry can cope only with a limited quantity of harvest (9,000 wet t y^{-1}); and a second in which we assume a double gathering of kelp that requires doubling the number of vessels. We are also assuming that each vessel is able to operate for 100 days.

For the concept based on the big Norwegian trawler, two vessels are simulated operating for the first 4 years and then another one is added until the end of the project to arrive at the total cumulative harvest of 27,000 t y^{-1}.

For each concept we provide sensitivity analysis varying not only the price of kelp, but also the quantity of kelp that can be collected and the cost of harvesting. For the French fishing vessels concept, we make the assumption that the quantity of kelp that can be collected can range from 10 to 16 t $d^{-1.}$, and the variable cost of harvesting from £400 to £600 d^{-1}. For the big Norwegian trawler, owing to the scarcity of information available, on the best of reasonable assumptions we consider operating costs fixed at £1,500 d^{-1} and the quantity of kelp collected in the range of 80-90 t d^{-1}.

In the following tables we report the results of the DCF. The indicators used to assess the profitability of the business are the Net Present Value (NPV) and the Internal Rate of Return (IRR). The NPV shows the present (discounted) net benefits (difference between revenues and costs), an indicator of the absolute finances the project generates, while the IRR shows the performance of the project in relative terms. Its value can be compared with the return from alternative investments.

If we assume to harvest kelp by using the smallest vessels at the rate of 15 t d^{-1}, a positive NPV cannot be achieved even at price of £40 t^{-1} for a total collection of 9,000 t y^{-1}. For all the combinations of prices and harvest proposed in the Table 32 the net benefits are negative. Similar considerations apply if in the DCF we model the gathering of a double quantity of kelp (Table 33).

Table 32. *NPV and IRR when harvesting with small vessels operating at cost of £500 d^{-1} and collecting up to 9,000 t of kelp from year 4 to year 30*

NPV		
Price (£t^{-1})	Harvest per vessel (t d^{-1})	
	10	***15***
30	-£2,488,459	-£1,249,799
40	-£1,662,686	-£11,138

IRR		
Price (£t^{-1})	Harvest per vessel (t d^{-1})	
	10	***15***
30		
40		3.39%

Table 33. *NPV and IRR when harvesting with small vessels operating at cost of £500 d^{-1} and collecting up to 18,000 t of kelp from year 4 to year 30*

NPV		
Price (£t^{-1})	Harvest per vessel (t d^{-1})	
	10	***15***
30	-£4,976,919	-£2,499,598
40	-£3,325,371	-£22,277

IRR		
Price (£t^{-1})	Harvest per vessel (t d^{-1})	
	10	***15***
30		
40		3.39%

From the previous figures emerges that a business investing in harvesting is facing a negative NPV in all the combinations of prices and harvest rate considered. It is easy to show that to make this investment more attractive, higher revenues must be generated. To get an IRR of at least 6% (a medium return for project in the agricultural sector) with a positive NPV (£319,171) under the harvesting scenario of t 9,000 y^{-1}, the quantity of kelp to be collected by each vessel must be 16 t d $^{-1}$ at the highest price of £40 t^{-1}, or keeping the harvest constrained at 15 t d^{-1}, the price of kelp should raise at least at £42 t^{-1} (under the latter scenario the NPV is equal to £236, 594). It is not possible to operate in profits at the price of £40 t^{-1} if harvest drops below 16 t d^{-1}.

Similar considerations apply to the scenario with a harvest of t 18,000 y^{-1}. No positive NPVs are achievable at the highest price of £40 t^{-1} and harvesting rate of t 15 d^{-1}. However, under the same harvesting rate, at price of £41 t^{-1} the NPV becomes positive (£225,455), and at price of £42 t^{-1}, as reported in Table 33, investing in seaweeds harvesting provides a return (IRR=5.66%) aligned to many agricultural projects. In particular, at price of £45 t^{-1} the net benefit overcomes £1 million, and at price of £47 t^{-1} the IRR goes over 10%. According to the sensitivity analysis, we can say that prices slightly higher than £40 t^{-1} make harvesting operations a profitable business and as remunerable as other non-risky investments in the primary sector (direct use of natural resources or exploit natural resources) generating a return of 5-6%.

Table 34. *Sensitivity analysis of NPV and IRR to kelp prices under the collection of t 18,000 y^{-1} at operating cost of £500 d^{-1}, harvest rate of t 15 d^{-1} per vessel, and discount rate of 3.5%*

Price (£t^{-1})	NPV	IRR	Price (£t^{-1})	NPV	IRR
38	-£485,971	0.93%	43	£720,920	6.71%
39	-£238,239	2.29%	44	£968, 652	7.71%
40	-£22,227	3.39%	45	£1,216,384	8.69%
41	£225,455	4.56%	46	£1,464,116	9.64%
42	£473,187	5.66%	47	£1,711,848	10.56%

The NPV and IRR shows high sensitivity to the operating costs: 10% variations in these costs significantly alter the profitability of the investment. In fact, at costs slightly higher than adopted in the assumptions, the NVP becomes negative, but at costs slightly lower the profitability increases enormously providing a return over 7% (Table 34). Considering there are uncertainties in the operating costs, a positive cumulative profitability would be predicted only for harvesting costs that are not higher than £500 d^{-1}. To get a positive NPV (£142, 878) and an IRR higher than 4% at the variable cost of £550 d^{-1}, the price of kelp must be 10% higher (£44 t^{-1}) than the maximum value assumed in this model. This result suggests negotiating with the industry a price higher than £40 t^{-1} to give better chance to the harvesting enterprise to achieve a positive return.

Table 35. *Sensitivity analysis of NPV and IRR to variations in the operating costs*

NPV and IRR at 15 t d^{-1} and £40 t^{-1}			NPV and IRR at 15 t d^{-1} and £42 t^{-1}		
Costs (£d^{-1})	NPV	IRR	Costs (£d^{-1})	NPV	IRR
400	£1,629,270	10.26%	400	£2,124,735	12.06%
450	£803,497	7.05%	450	£1,298,961	9.00%
500	-£22,227	3.39%	500	£473,187	5.66%
550	-£848, 050	-1.42%	550	-£352, 586	1.68%
600	-£1,673,824	-15.75%	600	-£1,178,360	-4.24%

When working out the DCF for the second concept (Norwegian trawler), it is feasible to achieve a return above 4% at the harvest rate of 80 t d^{-1} only if kelp price is above £43 t^{-1}, while similar results can be achieved at the standard market price of £40 t^{-1} when collecting 90 t d^{-1} (Table 35). From these results, as previously observed for the French vessel, it is reasonable to assume that agreeing with the kelp processing industry a price higher than £40 t^{-1} gives better chances of a more stable and profitable business.

It is reasonable to assume that some of the negative values reported in the Table 35 are caused by misleading deductions and/or assumptions introduced in the model, not confirmed by the owner of the trawler because of the impossibility to disclose confidential information.

Table 36. *NPV and IRR for harvesting with a Norwegian type vessel at operating cost of £1,500 d^{-1}*

NPV		
Price (£t^{-1})	**Harvest (t d^{-1})**	
	80	***90***
38	-£1,394,626	£190,638
40	-£727,146	£941,553
41	-£393,407	£1,317,010
42	-£59,667	£1,692,467
43	£274,073	£2,067,925
44	£607,813	£2,443,382
45	£941,553	£2,818,839

IRR		
Price (£t^{-1})	**Harvest (t d^{-1})**	
	80	***90***
38	2.05%	3.69%
40	2.76%	4.41%
41	3.1%	4.76%
42	3.44%	5.11%
43	3.77%	5.45%
44	4.09%	4.78%
45	4.41%	6.11%

6.4.4.2 Licensing of workboat operators

In this scenario we assume that the licence to harvest is obtained by the fishermen who are using their own vessels reclassified as workboat. The assumptions used for modelling the fishing vessel as a workboat are the same adopted in the single licence holder model, apart from the initial capital for the acquisition of the vessel that is excluded here. In the DCF only the depreciation and the reclassification costs of the vessel as workboat and annual inspections are considered. It is assumed that the <10 m vessels can collect from t 10 d^{-1} to t 15 d^{-1}, while the 10-12 metres vessels from t 20 d^{-1} to t 30 d^{-1}. The price of kelp is in the range £30 to £40 t^{-1}, and the operating costs are assumed to be £500 and £800 d^{-1}. Table 36 and Table 37 report the NPV for the two typologies of vessels classified according the operating cost.

Table 37. *NPV of a single fishing vessel operating as a workboat at the operating cost of £500 d^{-1}*

NPV		
Price (£t^{-1})	**Harvest per vessel (t d^{-1})**	
	10	***15***
30	-£307,635	-£84,171
40	-£158,659	£139,292

Table 38. *NPV of a single fishing vessel operating as a workboat at the operating cost of £800 d^{-1}*

NPV		
Price (£t^{-1})	**Harvest per vessel (t d^{-1})**	
	20	***30***
30	-£307,635	£139, 292
40	-£9,683	£586,219

From the Table 36 it is evident that small hold vessels (gathering up to t 15 d^{-1}) operating at cost of £500 d^{-1} have a positive net benefit only at the highest price and gathering rate, while vessels with bigger capacity (gathering between t 20-30 d^{-1}), even if characterised by higher operating cost (£800 d^{-1}), can provide an interesting return over 30 years (Table 37). The possibility to collect kelp at lesser rate (t 18 d^{-1}) could be supported only if the price of kelp was higher than £44 t^{-1}, while a price of £43 t^{-1} could sustain a reduced production rate of 19 t d^{-1}. The latter price-harvesting rate scenarios, if achievable, would extend the number of vessels suitable for harvesting; this should be promoted by a negotiation with the industry to gain a mark-up of at least £4 t^{-1} over the standard commercial price recorded in some EU markets.

It is likely that the majority of the 10-12 metres trawlers adopted in Scotland have a hold capacity not exceeding 7-8 ton (according to the judgment of McDuff Shipbuilder – Table 26). Under the assumptions that gathering occurs close to the main ports, allowing for three harvests per day, the average collection rate would be in the range 21 to 24 t d^{-1}. This would generate a positive net benefit in the order of £80,000- £260,000 in 30 years at the constant price of £40 t^{-1} as shown by the sensitivity analysis proposed in Table 38. From the same table emerges that at the constant price of £40 t^{-1} if the average harvesting rate of 25 t d^{-1} were achieved, this would generate each year a net rent over £15,000 (and a net present value of nearly £290,000 in 30 years) a figure that is aligned with the small scallop dredger profits (£16,600 as average of the last 10 years activity at 2012 GBP constant price), and higher than the under 10 metres trawlers (£10,100 as average of the last 10 years activity at 2012 GBP constant price).

Table 39. *Sensitivity analysis of NPV to kelp harvest at the constant price of £40 t^{-1} and operating cost of £800 d^{-1}.*

Harvest (t d^{-1})	**NPV**	**Harvest (t d^{-1})**	**NPV**
21	£49, 907	26	£347, 858
22	£109, 497	27	£407, 448
23	£169, 087	28	£467, 038
24	£228, 677	29	£526, 629
25	£288, 268	30	£586, 219

6.4.5 Estimate of the licence cost

As shown in Section 5, predicting costs of licensing processes is difficult since it is not possible to know what the sensitivities are until baseline surveys are undertaken, followed by impact assessment to understand the likely effects of a specifically defined harvesting activity and through discussion with the licensing authority and statutory consultees.

Moreover, licensing processes have cost implications on the development of activities offshore, and particularly for new activities, or an increase in scale of activity, that has not existed before. As experience grows, along with the understanding of ecological effects, it is likely that the costs of licensing will decrease over time. Initial proposals will inherently be more costly due to the greater 'burden of proof', which will inform subsequent developments.

Considering the difficulties to quantify in monetary terms the key steps of the licensing process outlined in the Section 5, an alternative approach can be adopted where the optimal cost of a licence is quantified as the discounted future rent (net benefits). In economics when considering the inter-temporal values of a resource, the optimal strategy for exploitation is to assess under what conditions the 'today' profit (economic rent) generated by a unit resource extraction is balanced by the expected future rent of keeping the resource undisturbed. This implies that if keeping the resource untouched provides higher profits in the future, it is opportune to reduce the 'today' rate of extraction. This mechanism is related to the temporal preferences of society having more or less impatience in the exploitation of a resource. This impatience is reflected in the market discount rates that are used to address decisions on the rate of extraction between present and future allocations.

Borrowing the fish quota system model, we could specify the annual value of a licence as the value of a one-year lease on the right to harvest. This is equal to the rent from the business, that is, the price of the harvest minus the marginal cost of harvesting (Clark, 1990). From the lease price it is possible to assess the value of holding the right of harvesting in perpetuity (i.e., the quota sale price or the capital value of the business), as the capitalisation of the expected rent at the market discount rate. In other words the value of the right to harvest should roughly equal the lease price divided by the market discount rate, assuming expected lease prices are relatively constant (Newell *et al.*, 2002).

Here we assess annual economic rent using the assumptions provided in the DCF and the licence cost as the amount of money to be paid to guarantee in perpetuity the rent at the nominal private discount rate (for environmental projects implemented in the EU this is on average equal to 5%). It is evident that the rent is a function of the price of kelp, cost of harvesting and the other variables previously introduced in the DCF. No information about the cost of monitoring are introduced here, owing to the difficulties to define in punctual ways costs and a reliable plan of monitoring. However, the information reported in Table 9 suggests that a monitoring plan of the impacts and recovery of the habitat for at least 5/6 years after harvesting could be prohibitive for single fishermen or a SME operating exclusively as gatherer without any subsidiary integration with the processing industry. Therefore, results are affected by the assumptions contained in the DCF. The figures below reported are extracted from some of the economic scenarios proposed in the DCF that we assume can be feasibly achieved.

Under the *single licence model* applied to the French vessel typology, we have found (see Table 34 and Table 35) that for operating costs of £500 d^{-1} and kelp prices of £41 t^{-1} and £42 t^{-1}, respectively, a net discounted profit (over 30 years) between £225,000 and £470,000 can be generated. Under this scenario that provides a return in the 6-7% interval, a net annual rent of £35,000 – £83,000 is produced. The acquisition of rights to harvest kelp in perpetuity, at the market interest rate of 5%, can be then estimated in £700,000 - 1,660,000. Under the assumption that the amount of harvest is 18,000 t y^{-1}, the annual lease price of a tonne of kelp can be quantified in £1.94 - £4.61.

Under the *single licence model* applied to the Norwegian vessel (see Table 35), at the harvesting rate of 90 t d^{-1} a net discounted profit (over 30 years) between £940,000 and £1,300,000 can be generated, if kelp prices were £40 t^{-1} and £41 t^{-1}, respectively. Under this scenario providing a return of 4-5%, an annual rent of £326,000 – £348,000 can be generated. The acquisition of rights to harvest kelp in perpetuity, at the market interest rate of 5%, can be then estimated in £6,520,000 - £6,960,000. Under the assumption that these finances can be generated at the harvest rate of 27,000 t y^{-1}, the annual lease price of a ton of kelp can be quantified in £12.1 – 12.9.

For the model based on *licensing of workboat operators,* the Table 37 provides evidence that vessels operating at costs of £500 d^{-1} at collection rate of 15 t d^{-1} and kelp price of £40 t^{-1} can generate a net benefit of £140,000 over 30 years. The annual rent is estimated at £7,500 (equivalent to £5 t^{-1}, under the average harvest of 1,500 t y^{-1}) and the value of the business, i.e. the acquisition of rights to harvest kelp in perpetuity at the interest rate of 5%, is estimated at £150,000.

For vessels operating at higher cost of £800 d^{-1}, under a kelp price of £40 t^{-1} there is evidence of a very broad net benefit in the range £50,000 – £600,000 (Tables 37 & 38). This broad interval depends on the quantity that can be feasibly harvested in a day, which in turn is a function of how close is the homeport to the resource (Section 6.1). We restrict the focus on a limited number of values among those proposed in the Table 39. Under the assumptions that 10 m trawlers in Scotland have a hold capacity not exceeding 7-8 t and can complete three harvest trips each day, the average collection rate would be in the range 21 to 24 t d^{-1}. This would generate a discounted net benefit in the order of £50,000 - £230,000 over 30 years at a discount rate of 3.5%. The annual average net rent is estimated at £2,700 – £12,400, and the acquisition of rights to harvest kelp in perpetuity, at the market interest rate of 5%, can be valued in the order of £54,000 - £248,000. Under the assumption that these finances can be generated at the harvest rate of 2,100 and 2,400 t y^{-1}, respectively, the annual lease price of a ton of kelp can be quantified in £1.28 –£5.17.

Summarising the annual licence can be very variable depending on the concept used. However, for the small fishing vessels it seems to be reasonably quantified in the interval £2,000-£10,000, while for the sole harvester model it can be in the interval £30,000 - £90,000 (French vessel type), and in the range £300,000 to £350,000 for the Norwegian vessel concept. The annual lease price of 1 ton of kelp should be in the range £1 to £5, when the model based on licensing local fishing vessels, or a sole harvester operating under the French vessel typology, is considered. In the case of the *single licence* allowed to a harvester operating by the Norwegian trawler this price is more than double (£12-£13). A summary of findings is reported in the Table 40.

It is evident the net rent must reflect the net benefits of the operations, therefore cost of monitoring should be considered. Following the estimated cost of monitoring proposed in the Table 8 and the Gigha case study in Section 4, it seems evident that only harvesting based on the Norwegian concept can cope with these costs. This suggests, as more explicitly reported in the following sections, that harvesting should be integrated to kelp processing so that monitoring can be more feasibly embedded into the value chain.

Table 40. *Cost of licence for difference concepts.*

Concept	**Economic Rent or profit**	**Tons of kelp harvested per year**	**Annual cost of leasing a licence per ton of kelp**	**Licence cost as right of harvesting in perpetuity at 5% interest rate**
Single licence holder – French type vessel Operating cost £500 d^{-1} Kelp price £41 and £42 t^{-1}	£35,000 £83,000	18,000	£1.94 £4.61	£700,000 £1,660,000
Single licence holder – Norwegian type vessel Kelp price £40 t^{-1} and £41 t^{-1}	£326,000 £348,000	27,000	£12.1 £12.9	£6,520,000 £6,960,000
Licencing workboat operators (at operating costs of £500 d^{-1} and price of £40 t^{-1})	£7,500	1,500	£5	£150,000
Licencing workboat operators (at operating costs of £800 d^{-1} and price of £40 t^{-1})	£2,700 £12,400	2,100 2,400	£1.28 £5.17	£54,000 £248,000

6.5 Value Chain

The following factors should also be considered when assessing competitiveness of the harvesting operations, especially if this were integrated into the value chain.

6.5.1 The total value across the Value Chain.

Scottish seaweed harvesting appears to be relatively low value at the raw material stage, but very high value in downstream effects. For example, at £40 t^{-1} of wet seaweed:

- A 10,000 t industry would be of negligible total value (£400,000) and may not be proportionate to the risks it may pose to the marine (operating and natural) environment, or the costs to mitigate and monitor such activity.
- Even a large harvesting operation of 50,000 t may at such a price come to £2m (in fact, Scottish harvesting costs would likely be higher, meaning primary harvesting would likely be closer to £3-5m).
- However, if the sole intention is that a very high value manufacturing and pharmaceutical industry of a scale in the £100m (the range may be between £100-500m after 10 years) can be enabled through that relatively low value harvesting, then appropriate compliance and monitoring / management costs should be viable over the total Value Chain.
- Relying on the downstream value addition may not always be relevant, but in this case the licence-holder is likely to be the same downstream partner, without whom it is unlikely such operations would take place (i.e. it is assumed that individual operators would not hold such a licence in the same manner as a fishing fleet).

6.5.2 Alternatives to Scottish harvesting, and supply chain dependencies.

In the case of potential for harvesting *Laminaria hyperborea*, due to quality and freshness factors if Scotland were unable to provide large volumes, the processing and high quality manufacturing operations (the bulk of the supply chain) would likely move to countries best placed to provide volumes. While this may be sub-optimal for potential operators, it is credible that this should be the case given the operating models elsewhere (e.g. France and Norway). In favour of Scottish harvesting are factors such as:

- *Quality and time-dependence: Laminaria hyperborea* in Scotland is considered to be particularly appropriate for high quality alginate processing. This affects the substitutability of raw material from one source to another.
- *Volume:* Scottish waters are considered to have large stocks of *Laminaria* that may be harvested with it is believed, tolerable impacts to stocks and the natural environment.
- *Cultivation: Laminaria hyperborea* is not presently cultivated in Scotland although experiments are being undertaken. Cultivation cannot at present replace wild harvesting.

- *Provenance:* Sustainable harvesting methods are increasingly required by customers as well as regulators. This differentiation of product may command a premium but it is not necessarily in proportion to the extra investment required.

Other seaweed varieties harvested at larger scale (e.g. *Laminaria digitata*) will be viable depending on similar competitiveness, value chain and provenance. The lower the quality and provenance requirements, the higher the degree of substitutability and price sensitivity. Many segments of the seaweed market have been left to China as well as other producers because of price competitiveness but locally supplying specific requirements for higher value processing can still be viable (Section 6.5.1).

6.5.3 Value chain feasibility

The licensing process will require the licence-holder to actively manage the resource being used and demonstrate impact, whether using fishing boat-type workboats and crew as suppliers under contract, or fully vertically integrated workboats.

On the basis of this active management requirement, the economic feasibility is better considered across the full integrated processing chain (Figure 39).

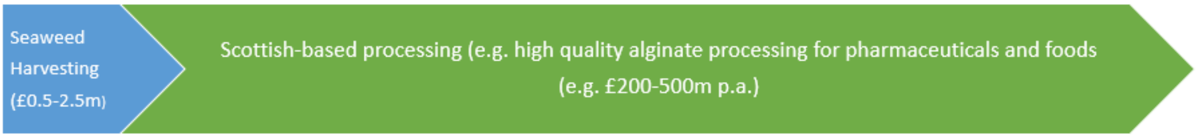

Figure 39. *Economic Value of Harvesting and Processing (illustrative, not to scale)*

Under the expected licence-holder arrangement, the total attainable (turnover) value may be some 100 times greater than the harvested value. In such a scenario, the economic benefits for both the commercial operator should justify a proportionate management regime which can demonstrate environmental standards (impacts of harvesting) to the satisfaction of customers and regulators.

Further details of a market assessment submitted by a private firm during the consultation phase of this project can be found in Annex C (reproduced with their permission), which highlights the estimate value that the company hope to generate from kelp harvesting.

6.5.4 Competitiveness

It is expected that the benefits of harvesting seaweed in Scotland (quality, provenance, geographic proximity of operations to harvesting, lack of full substitutability from other supply sources) would allow for a higher initial harvesting cost in a start-up phase. However, at some point this higher harvesting cost or restriction on significant volume harvesting would likely make Scottish harvesting, and therefore Scottish high quality processing, unviable.

The key test is that the downstream processors may need to judge whether for quality, proximity and operational reasons a given price may be tolerable, not that the Scottish harvesting is not viable unless it can compete on price with competitors. For example, if the international price is £40 t^{-1} but the Scottish cost was higher at e.g. £60 t^{-1}, there may still be good reasons for a processor to harvest in Scotland, given that the harvesting cost of raw material will be a relatively small portion of total operational costs. Alternatively, if the processor decides to buy raw material form a third party (fishermen) harvesting locally at higher than international price, under certain conditions it would be economically viable to do that rather than importing (Section 6.3).

Finally, licencing and monitoring costs should therefore be as efficient as possible but so as not to unduly deter high value development and processing operations, but must be fit for purpose. This is the reason why a detailed analysis of the DCF of the enterprise harvesting seaweeds can help defining the optimal licence cost. Evidence of sustainable production will be increasingly important for commercial reasons as much as for regulatory ones, Scottish provenance and quality is a widely utilised selling point for Scottish food and drink products.

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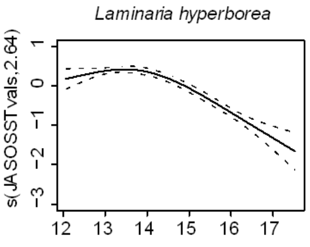
ANNEX A: MODELLING KELP DISTRIBUTION AND BIOMASS

A.1 Kelp habitat suitability models

The forms of the suitability models are shown in Figure A1 to Figure A4. Each panel in these two figures shows the pattern of occurrence of the kelp across ranges of depth (shallow at the top of the plot) and wave exposure (wave exposed to the right and wave sheltered to the left). The plots show the affinity of tangle, *Laminaria hyperborea*, for wave-exposed conditions in areas of low chlorophyll concentrations, and the greater depth penetration in the clearer waters associated with reduced chlorophyll. *Laminaria hyperborea* showed a decline in log likelihood of presence of 1.5 units (equivalent to a 4.5-fold decline) from 13°C to 16°C average summer temperatures (Figure A1, top right).

Sugar kelp, *Saccharina latissima*, was much more associated with wave-sheltered conditions (Figure A2), with depth penetration less sensitive to chlorophyll concentration than *Laminaria hyperborea*. *Saccharina latissima* was also less sensitive to temperature than *Laminaria hyperborea* between 13°C to 16°C but showed an accelerated decline from 16 to 17°C (Figure A2 top right). *Laminaria digitata* (Figure A3) was associated with the shallowest depths, most likely to be present at the surface and generally in less than 5m depth. This species was similarly likely to be present across all levels of wave exposure and chlorophyll concentrations and temperature between 12°C and 17°C. *Saccorhiza polyschides* (furbellows, Figure A4) was associated with greater depths (0-25 m in 1 mg/m^3) and was most likely to be found in areas of intermediate wave exposure. This species was the most sensitive to chlorophyll concentration of the four kelp species modelled.

Figure A1. *Habitat suitability model for* Laminaria hyperborea*. Intensity of green shading shows likelihood of presence across gradients of depth (vertical) and wave exposure (horizontal) at different temperatures and chlorophyll concentrations.*



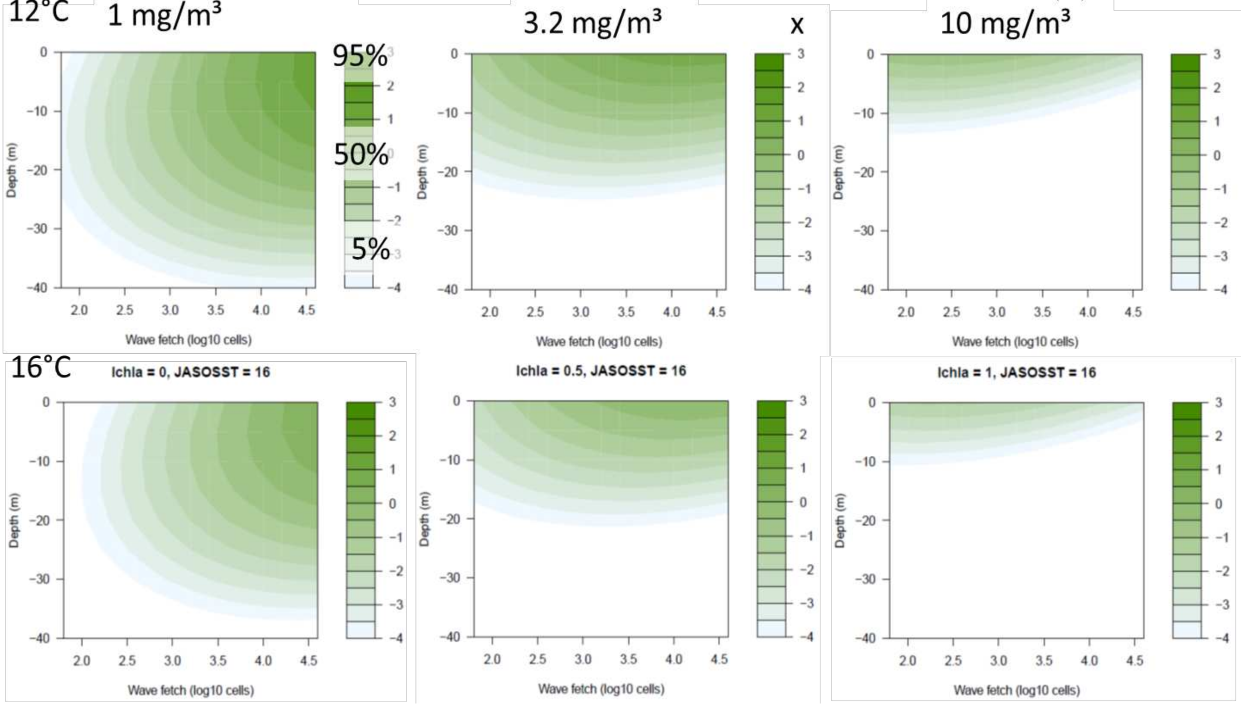
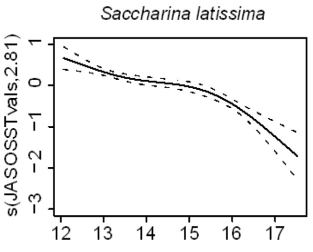


Figure A2. *Habitat suitability model for* Saccharina latissima*. As in Fig. A1, intensity of red shading shows likelihood of presence across gradients of depth (vertical) and wave exposure (horizontal) at different temperatures and chlorophyll concentrations.*



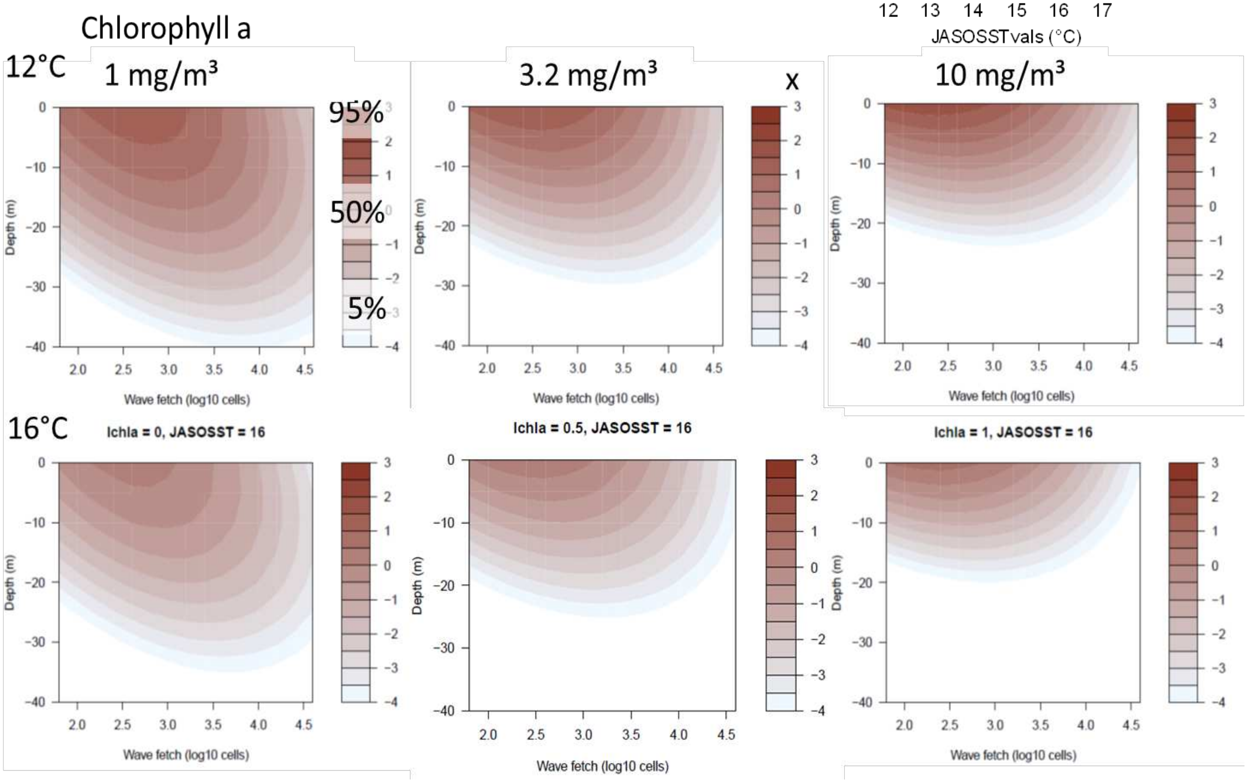
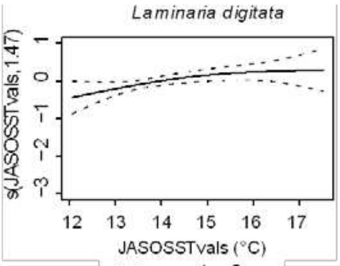


***Figure A3**. Habitat suitability model for* Laminaria digitata*. As in Fig. A1, intensity of brown shading shows likelihood of presence across gradients of depth (vertical) and wave exposure (horizontal) at different temperatures and chlorophyll concentrations.*



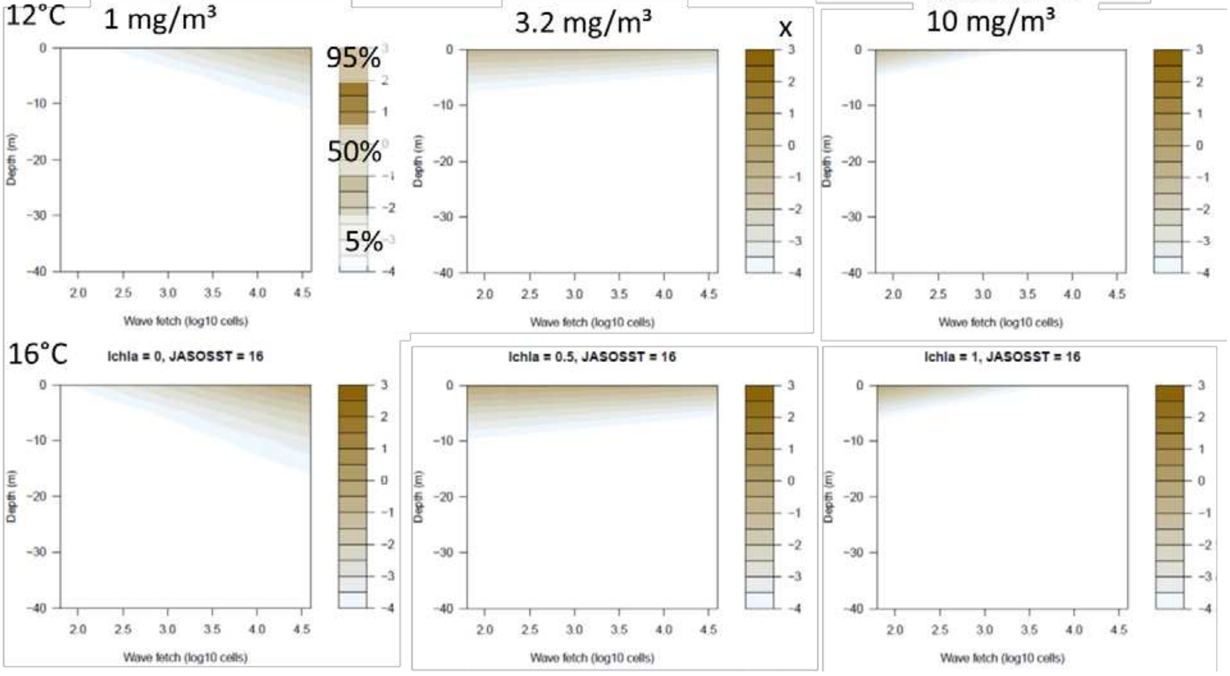
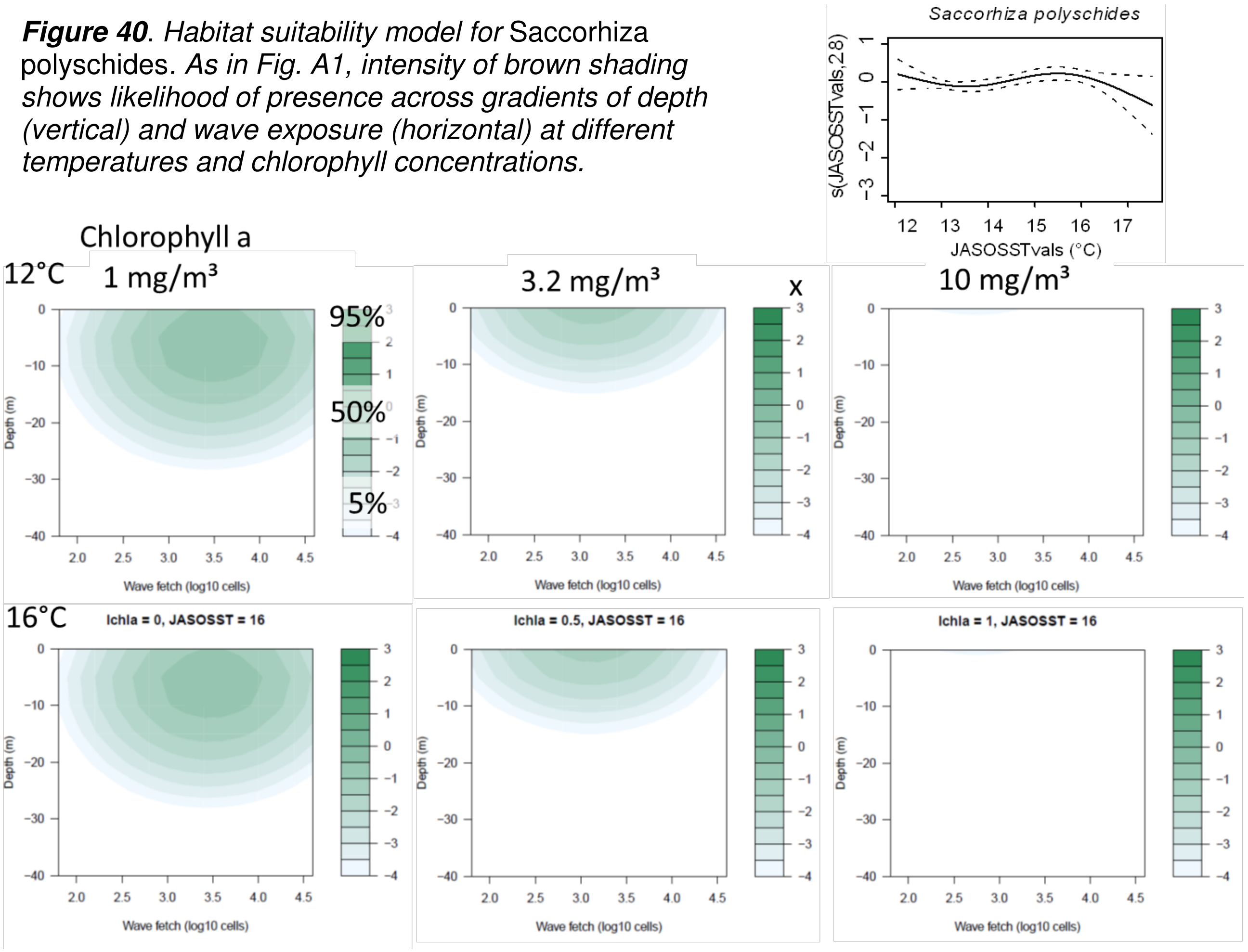


***Figure 40**. Habitat suitability model for* Saccorhiza polyschides*. As in Fig. A1, intensity of brown shading shows likelihood of presence across gradients of depth (vertical) and wave exposure (horizontal) at different temperatures and chlorophyll concentrations.*



A.1.1 Converting presence to biomass

As each SACFOR category is represented a different level of abundance, it was possible to estimate the total biomass for those species with information on plant size and weight (*Laminaria hyperborea* and *Saccharina latissima* from data in this report; *Saccorhiza polyschides* and *Laminaria digitata* from published studies) by summing the products of the probability of each category multiplied by an assigned biomass or percentage cover value for that category, across all the categories. Estimates of biomass were made for each grid cell and summed across specified regions to give regional totals.

Using this modelling approach, the relative proportions of kelp in each abundance class scale with the likelihood of presence of kelp (Figure A5). Above 95% likelihood of finding kelp (a log odds value of 3), most kelp is predicted to be abundant or superabundant, while in places where kelp is only 20% likely to be present, abundance is predicted to be common or below.

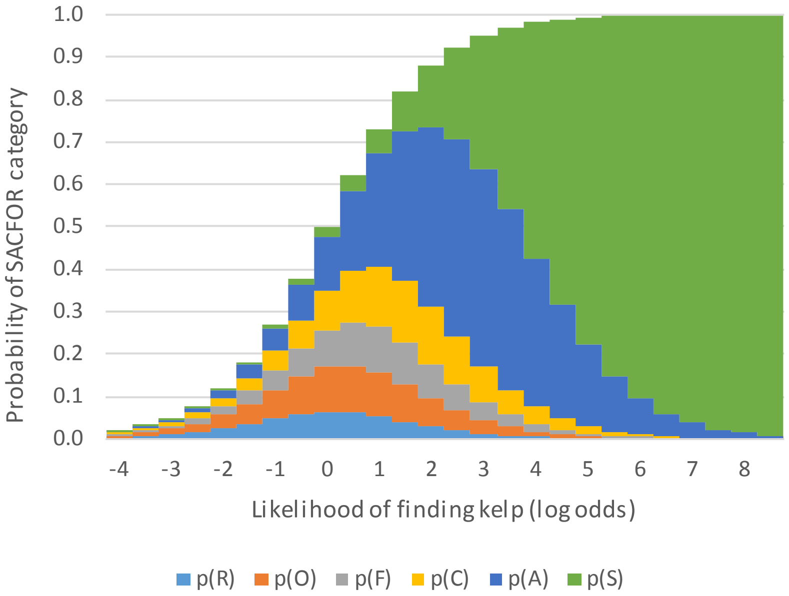


***Figure A5**. The probability of abundance classes for* Laminaria hyperborea *as a function of the likelihood of the species occurring in surveys.*

Converting these abundance classes to biomass values requires an understanding of how plant biomass per unit area scales with percentage cover or density of plants per unit area. Kain (1977) gave a maximum density of 24 kg/m^2 for *Laminaria hyperborea* wet mass across seven sites in West Scotland and the Isle of Man, at Port Erin and in Cuan Sound on Seil. The latter site is an unusual location for *Laminaria hyperborea* being so wave-sheltered, but with a relatively high tidal flow, perhaps resulting in larger than average sized plants. Taking this value as the biomass for maximum cover or maximum density allowed the estimation of biomass for each SACFOR category, scaled by percentage cover (Table A1, Biomass Scale 1) or by plant density at the midpoint of each category (Table A1, Biomass Scale 2).

Values for biomass densities of *Laminaria hyperborea* and *Saccharina latissima* were obtained from measurements from diver collected samples in this and recent studies in Scotland (sections A.2.1 and A.2.2). Biomass densities of *Laminaria digitata* and *Saccorhiza polyschides* were obtained from published studies. For *Laminaria digitata*, the work of Gevaert *et al.* (2008) found populations of this species with plant densities of up to 19 plants per m^2 (average 18 plants per m^2) and 3.0 kg/m^2 fresh weight of thallus material for dense plots. The 3.0 kg/m^2 value is taken as the upper limit for conversion of presence to biomass for *Laminaria digitata* in Super-Abundant and Abundant categories.

Saccorhiza polyschides is a highly seasonal species: a fast growing annual plant (Norton and Burrows 1969) producing fronds in spring and summer that decay rapidly after the onset of reproduction in October. Values for biomass for this species can only apply to the period when plants are present in the summer. Biomass values for the UK are not available, but Fernandez (2011) reported peaks of 500g DW/m^2 in dense stands in Northern Spain when the species was abundant in the 1970s, equivalent to 3.3 kg/m^2 fresh weight assuming 15% dry matter content of fresh material. The value used for the species here is 3.0kg/m^2.

Table A1. *Biomass for each abundance category for kelp species scaled to plant density or percentage cover.*

Category	[**S**] Super-Abundant	[**A**] Abundant	[**C**] Common	[**F**] Frequent	[**O**] Occasional	[**R**] Rare
Density (plants/m^2)	>9 /m^2	1-9 /m^2	1-9 /10m^2	1-9 /100m^2	1-9 /1,000m^2	<1 /1,000m^2
midpoint	15 /m^2	5 /m^2	0.5 /m^2	0.05/m^2	0.005/m^2	0.0005/m^2
Percentage cover	>80%	40-79%	20-40%	10-20%	5-9%	1-5% or density
midpoint	90%	60%	30%	15%	7.5%	2.5%
Biomass scales (kg/m^2)						
Laminaria hyperborea (data: this study)						
Scale 1 (cover-scaled)	28	12	6	3	1	0.2
Scale 2 (density-scaled)	25	8.33	0.833	0.0833	0.0083	0.0016
Scale 2 modified	25	25	0.833	0.0833	0.0083	0.0016
Saccharina latissima (data: this study)						
Scale 3 (density-scaled)	6	6	0.2	0.02	0.002	0.0002
Laminaria digitata. Scale 4 (Gavaert et al., 2008)	3	3	0.3	0.03	0.003	0.0003
Saccorhiza polyschides (Fernandez 2011)	3	3	0.3	0.03	0.003	0.0003

A.2 Model validation and refinement

Comparison with diver survey data and literature values

Plant size and density information collected during diver surveys for *Laminaria hyperborea* and *Saccharina latissima* for this project were used to refine and improve initial estimates of biomass scaled to abundance values. These data were supplemented by information on plant size, percentage cover and biomass from locations in southwest England and Wales, collected for other projects by Dan Smale and Pippa Moore. Data from southern UK are included here for comparison and model improvement.

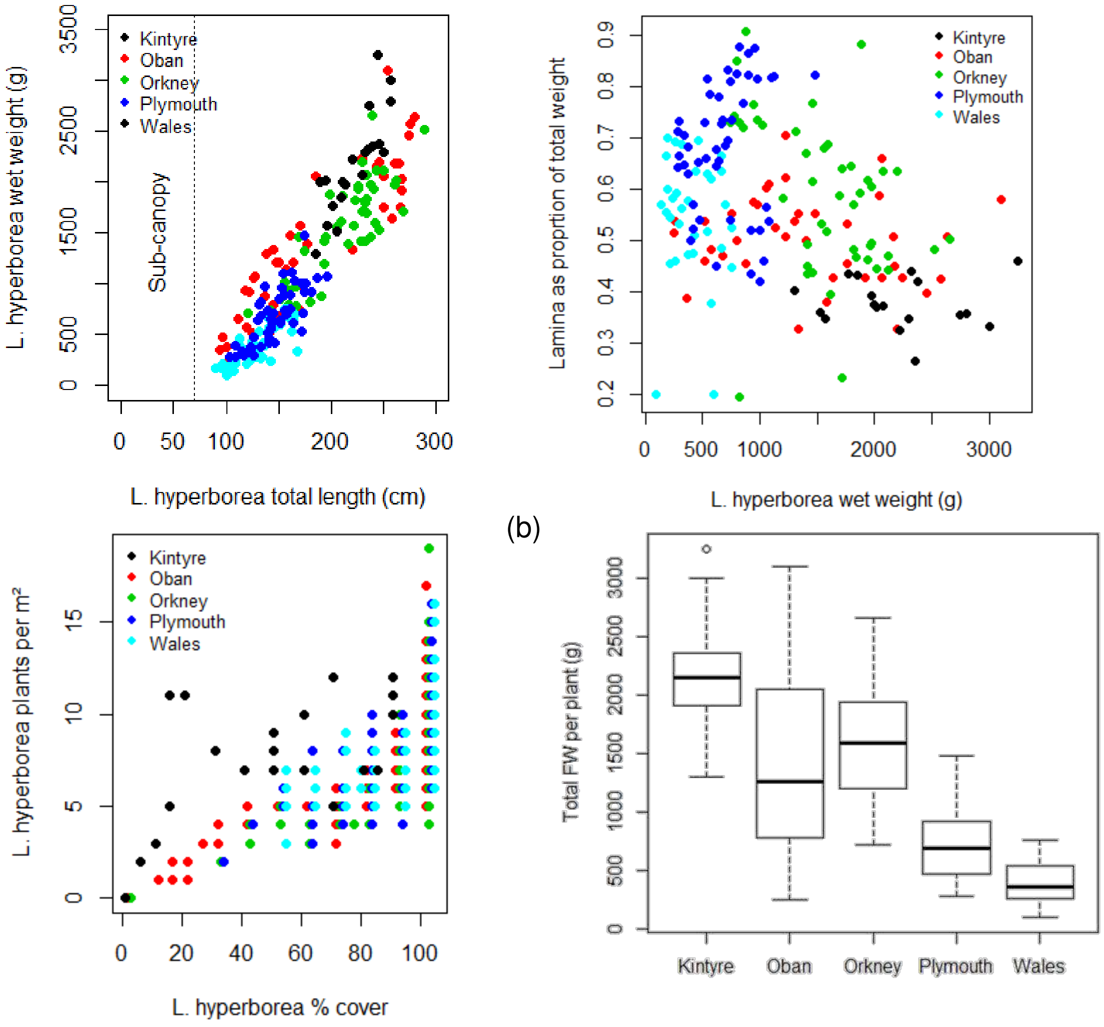
A.2.1 Laminaria hyperborea

For *Laminaria hyperborea,* plant sizes ranged from 0.1 to 3 kg in fresh weight and from 90cm to 300cm in length (Figure A6a) with plants in Scotland reaching much larger maximum sizes than those in England and Wales (Figure A6d). Sub-canopy plants less than 70cm in length were excluded. The weight of the blades (or lamina) was directly proportional to the length of the plants, and typically formed 50-80% of the total weight (Figure A6b), albeit with some variation among sampling locations. Percentage cover and the number of plants per unit area correlated strongly for sparse populations (Figure 8c), reaching 100% cover at around 7 plants per m^2. Complete cover (100%) covered a wide range of plant densities (4-17 plants per m^2). The overall relationship between cover and density was similar across regions.

Estimation of the biomass of *Laminaria hyperborea* plants per unit area from the diver-collected data was done in two ways: (1) using regional average plant weights (Figure A6d) multiplied by number of plants in each quadrat (Figure A6c), then averaging the per-quadrat estimates of plant biomass (Figure A8d) to give a site-specific biomass density; and (2) by multiplying location-specific average plant density by location-specific average plant weight (Figure A7a). Uncertainty for the first method was expressed as the standard deviation and standard error of the average total plant weight per quadrat, but this approach did not account for the variation in weight among individual plants at each location. For the second approach, the separate standard deviations and standard errors for the mean plant sizes and mean plant densities per location were combined using the formula for the propagation of uncertainties for products. Thus standard deviation for estimated biomass is a combination of the contributing means and standard deviations:

$$SD_b = \bar{d} \cdot \bar{w} \sqrt{\left(SD_d/\bar{d}\right)^2 + (SD_w/\bar{w})^2} \ ,$$

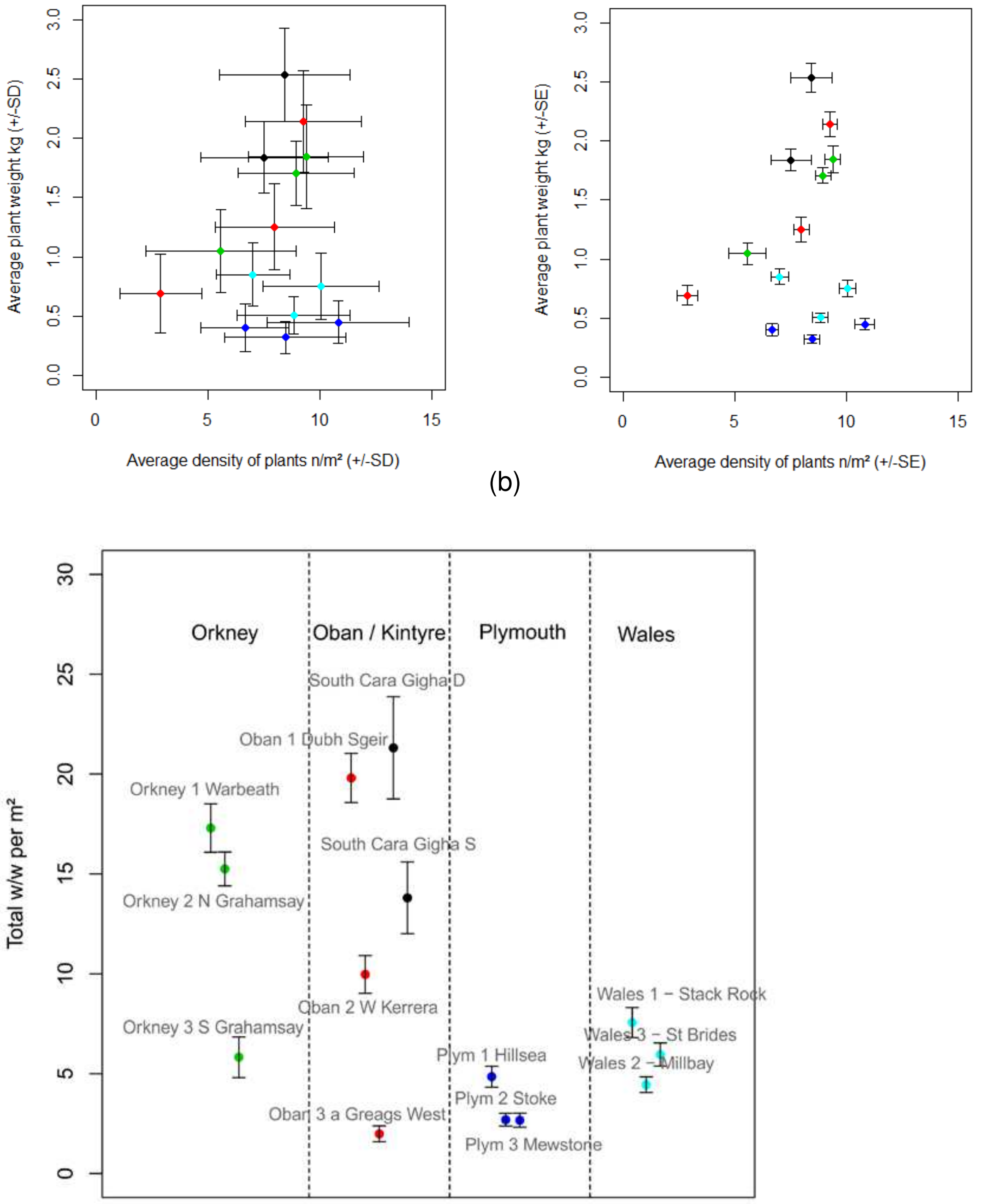
where b is biomass per m^2, d is density as number of plants per m^2, and w is the weight of individual plants in kg; with the same equation giving the standard error of estimated biomass by substituting SE for SD.



(a) (b)

(c) (d)

Figure A6. Laminaria hyperborea *collected in UK diver surveys: (a) fresh weight versus total length; (b) weight of lamina as a proportion of total weight; (c) the relationship between plant density and percentage cover in* $1m^2$ *quadrats; (d) the distribution of plant fresh weights (FW g) in each region.*



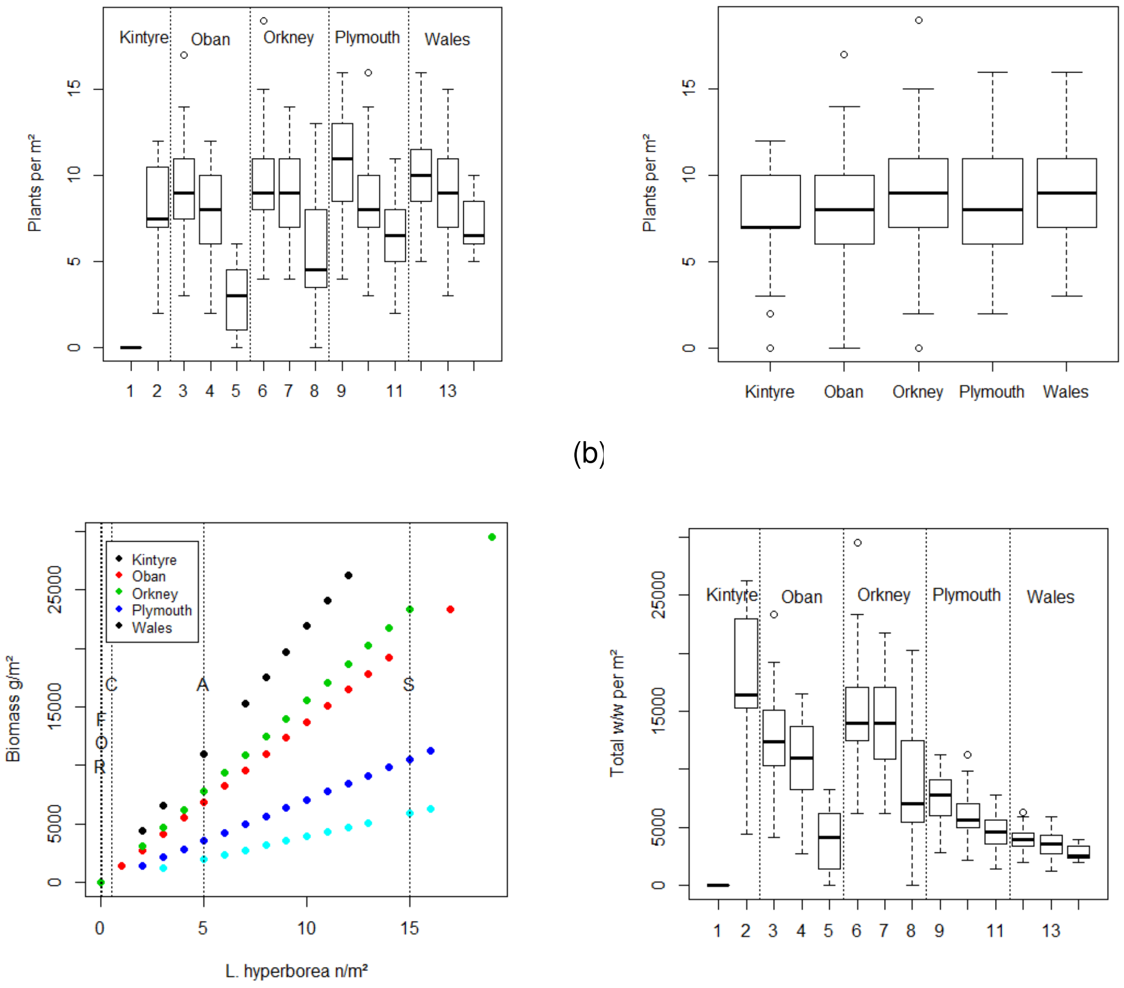
(a)

(b)

(c)

***Figure A7**. Laminaria hyperborea collected in UK diver surveys: (a) average weight per plant versus average number of plants per quadrat with error bars showing standard deviations; (b) as (a) but with error bars showing standard errors of estimates for plant weight and density; (c) estimated of biomass density as wet weight per m^2 with standard error bars from combined averaged plant size and density.*

Ranges of estimates for biomass (fresh weight) per m^2 estimates for each survey location (Figure A8d) values were within the 0 to 25kg/m^2 range of values reported by Kain (1977).



(a) (b)

(c) (d)

Figure A8. *Laminaria hyperborea collected in UK diver surveys: (a) plant density per location; (b) plant density per region; (c) plant biomass obtained by multiplying regional average plant sizes with plant density versus plant density per 1m*^{2} *quadrat. Midpoint densities for each SACFOR category are shown as dotted vertical lines; (d) Estimated biomass per quadrat across sites.*

The next step was to compare observed values for biomass per unit area from diver-surveyed locations with those predicted by the model for the same locations. Biomass scale 1 (Table A1) values for each category were used to convert the predicted likelihood of kelp presence to biomass across the whole UK model domain. Locations surveyed in this study, supplemented by recent data collected by Dan Smale and Pippa Moore since 2015, were used to extract predicted biomass values from the mapped data. It became clear that the 200-m scale of the larger model did not effectively give the depth of diver survey locations, so depth values extracted from maps were replaced with the actual depth of each survey. Likelihood of kelp presence was then recalculated using map-derived estimates of temperature, chlorophyll concentrations and wave exposure and survey-specific depth.

Combining the revised likelihoods with biomass per abundance category once more gave more exactly comparable estimates.

Given that the two methods of estimating biomass were entirely independently derived, the correspondence between the two estimates was reassuring (Figure A9). With biomass scale 1 (Table A1) using percentage cover associated with each abundance category to scale biomass per category from zero to a maximum of 28kg/m^2, the kelp suitability model consistently under-predicted kelp biomass: suitability model predictions of biomass using biomass scale 1 were between 2 and 7 kg/m^2 and were 43% of those estimated from locally determined plant densities and regional average plant sizes.

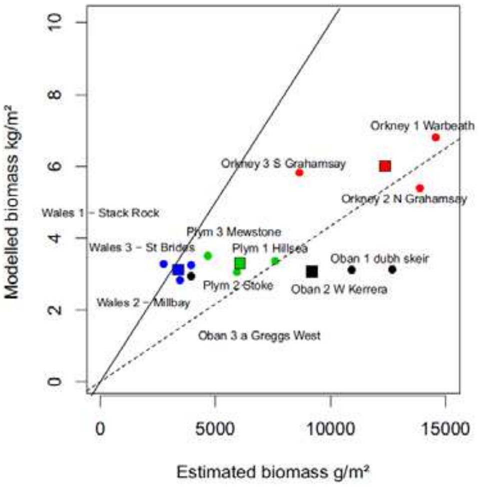
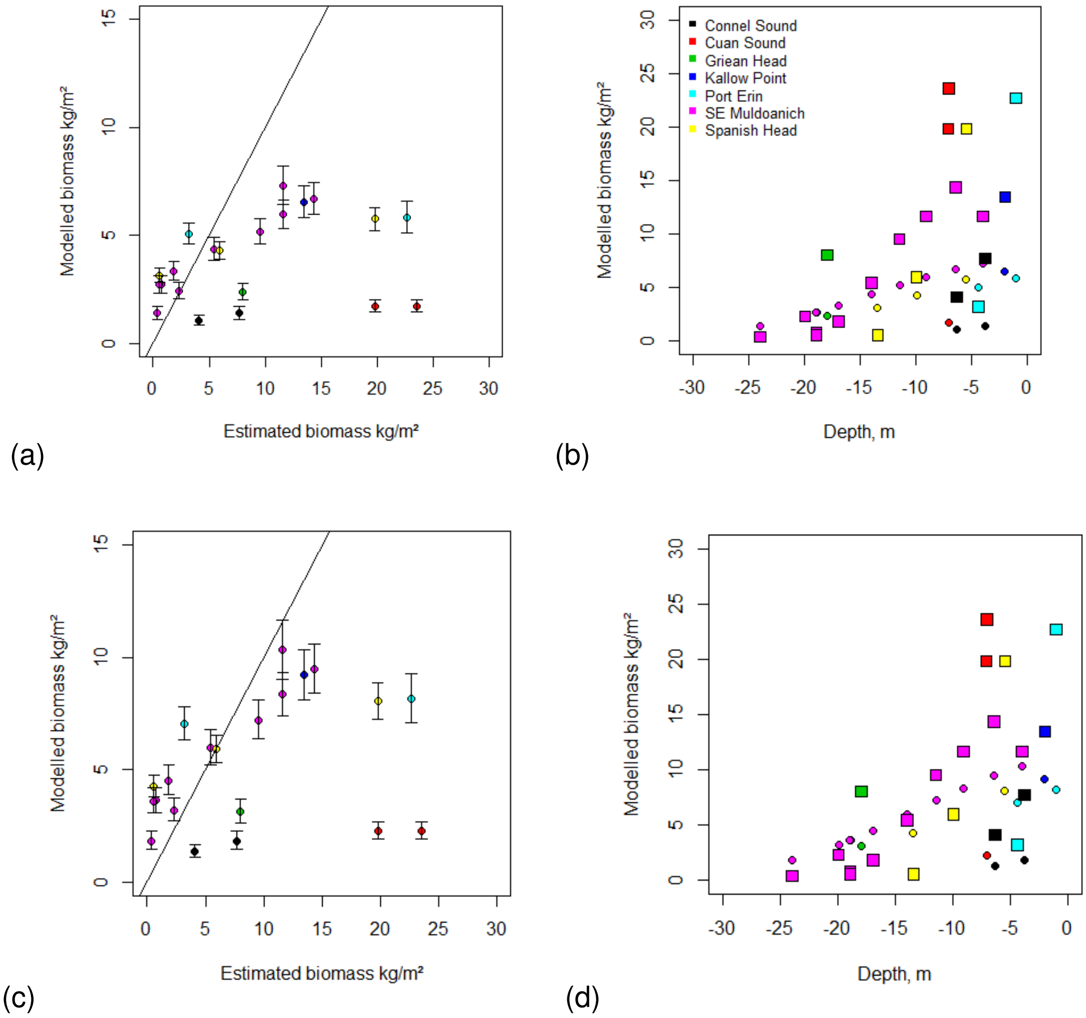


Figure A9. Laminaria hyperborea *collected in UK diver surveys. Comparison between biomass estimated from local average plant size and plant density (x-axis) and biomass predicted by the UK-scale kelp habitat suitability model using biomass scale 1. The no-intercept regression model (dotted line) had an* R^2 *of 0.86 (Model estimate = 0.000434 (+/- 0.000050 standard error) x local estimate). Circles show estimates for survey locations and squares show averages across the three locations in each region.*

Habitat suitability model predictions for biomass were further produced for locations reported in Kain (1977), using observed biomass data extracted from Kain's Figure 1. Comparison between modelled and observed biomass per unit area again showed underestimation of kelp biomass on average, especially in shallow areas with over-prediction biomass at greater depths, evident in data from Barra (SE Muldoanich, Figure A10b). Both the comparisons with diver survey data and those from the literature suggested that the biomass estimates used for each category were too small in Scale 1.

This under-fitting suggested that modification was needed to the biomass scaling relationship. Scaling biomass to the plant density instead of percentage cover (Biomass Scale 2, Table A1) did not alter the fit, but increasing the biomass for the "Abundant" category to 25 kg/m^2 did substantially improve the fit of the model to both Kain's data and the diver surveys (Figure A11).



(a) (b) (c) (d)

Figure A10. Laminaria hyperborea *biomass per unit area estimates from Kain (1977). Biomass Scale1: (a) versus modelled biomass (y-axis) for the same locations and depths, with error bars derived from the standard errors of GAM model estimates, and (b) against depth (squares, observations; circles, model predictions). (c, d) as (a, b) but using Biomass Scale 2 modified.*

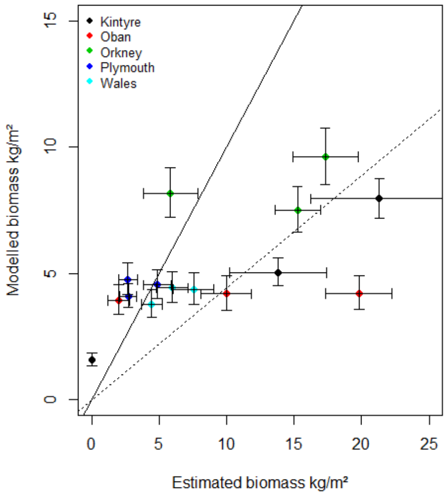
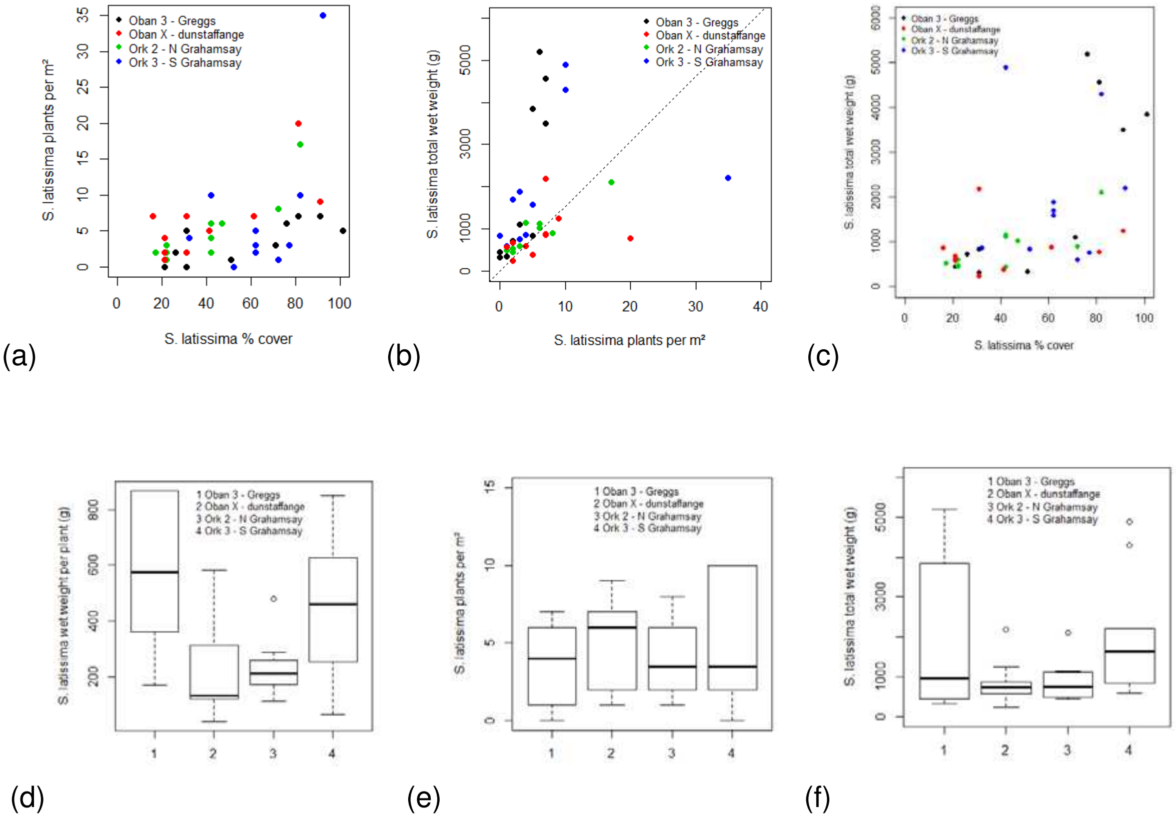


Figure A11. Laminaria hyperborea *collected in UK diver surveys. Model predictions (y-axis) versus estimated biomass (x-axis) for Biomass Scale 2 modified. Error bars show approximate 95% confidence intervals: on the x-axis as 2 x standard error of the mean biomass estimated from site-specific average plant sizes and plant densities (R^2=0.758, b=0.443 +/-0.064).*

A.2.2 Saccharina latissima



(a) (b) (c)

(d) (e) (f)

Figure A12. Saccharina latissima: *supplementary data showing (a) density and % cover in quadrats, (b) total plant weight versus density per quadrat (R^2 0.41, b=153 +/- 28), (c) total weight of plants versus % cover, and boxplots of (d) estimated weight per plant from total weight divided by number of plants and (e) plant density per quadrat.*

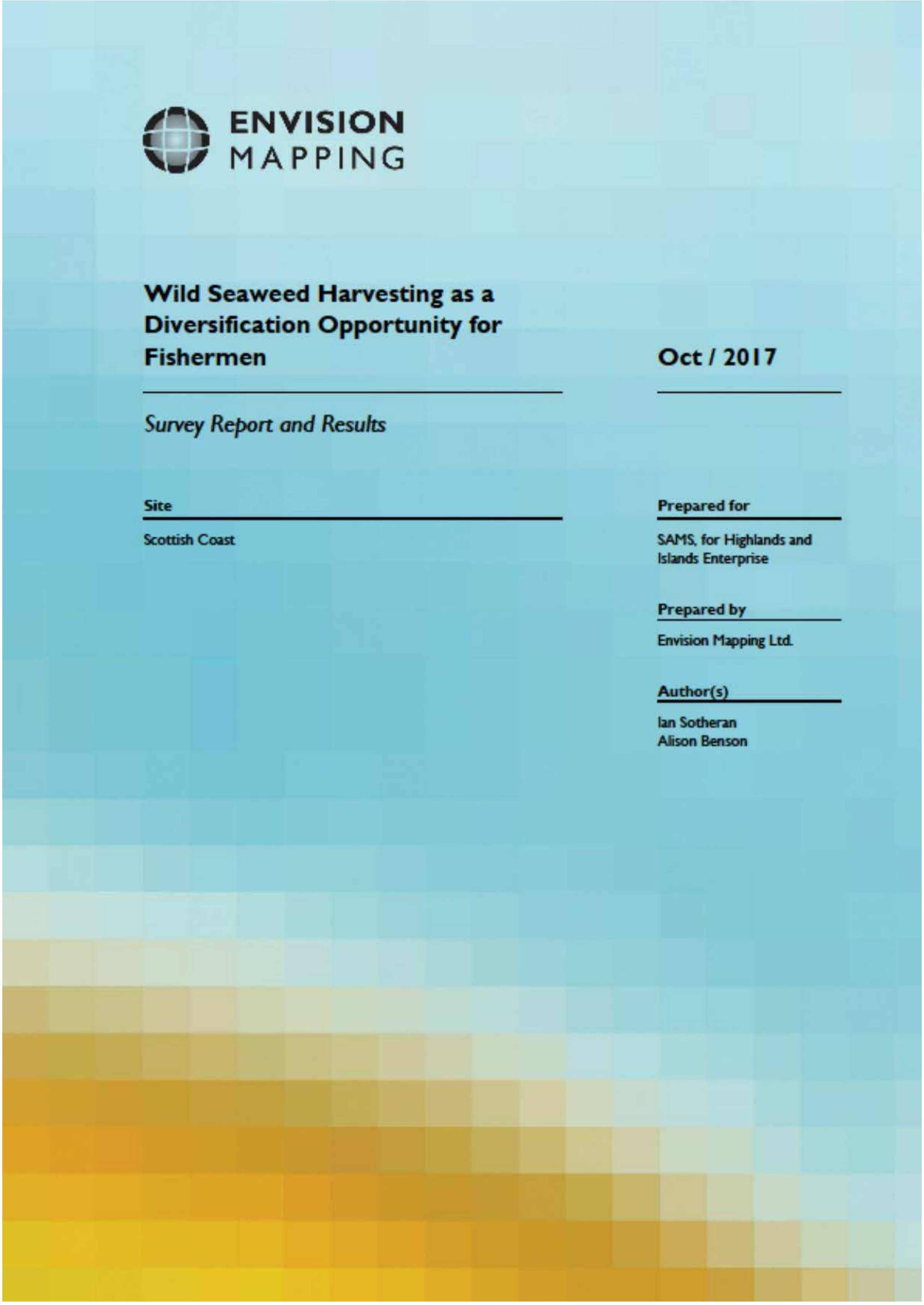
Diver-surveys in Kintyre and Orkney in 2017 for this report did not produce size and density estimates for *Saccharina latissima* since only occasional plants of this species were seen at the dive locations, but surveys at the nearby sites in Orkney and around Oban in 2015 and 2016 gave estimates of plant sizes, density per m^2 and biomass per m^2. *Saccharina latissima* plants were much smaller (0 to 0.8 kg, Figure A12d) than *Laminaria hyperborea* plants (0 to 2.5 kg, Figure A6d), and had a lower range of biomass densities (0 to 5 kg versus 0 to 25 kg). The observed range of values in this set, the dependence of total biomass on plant density (Figure A6b), suggested a biomass scale (Scale 3, Table A1) with a maximum of 6 kg/m^2. The lack of validation data for the predictive model for biomass for this species means that the values produced as estimates for biomass over larger areas should be seen as indicative only.

ANNEX B: SITE SURVEY REPORTS

The following report was completed by Envision Mapping Ltd. on behalf of SRSL.

It details the vessel based acoustic and drop down camera surveys completed as part of this project.

The report is present as an embedded .pdf in the electronic version of this document. Double clicking on the report cover below will open the Envision Report.



ENVISION
MAPPING

Wild Seaweed Harvesting as a Diversification Opportunity for Fishermen

Oct / 2017

Survey Report and Results

Site

Scottish Coast

Prepared for

SAMS, for Highlands and
Islands Enterprise

Prepared by

Envision Mapping Ltd.

Author(s)

Ian Sotheran
Alison Benson

Diver-based surveys for WILDWEED

The aims of the WILDWEED diving surveys is to collect in situ data on kelp abundance and percent cover and to sample representative kelp plants to generate data on canopy height and biomass. These data will be used to inform and ground-truth modelling activities and will be directly linked to acoustic and towed video survey work.

Activities to date

Tuesday 29th August

Planning meeting held at SAMS to develop sampling protocol and finalise dive sites and logistics. In attendance were Dr Martin Sayer, Prof Mike Burrows, Dr Dan Smale and Dr Pippa Moore.

Friday 1st September

Initial visit to Tayinloan to scope out logistics and diving safety aspects for working off Isle of Gigha. Development of risk assessments and operational plan for diving work. In attendance were Dr Dan Smale and Dr Pippa Moore and 3 NFSD technical staff.

Monday 4th September

Training dive: methods development and cross-calibration of density and percent cover estimates between scientists and technical support staff. Location was North Grahamsay in Orkney and in attendance were Dr Dan Smale and Dr Pippa Moore and 3 NFSD technical staff.

Wednesday 6th September

Data collection at site 1 in Orkney. Four divers completed two distinct operations to collect in situ data on kelp abundance and percent cover at 2 different depths (10 and 5 m bcd). Sixteen 1 x m quadrats were sampled and 10 replicate canopy-forming plants were collected from each depth. Plants were returned to the laboratory and analysed to quantify stipe biomass, blade biomass, stipe length and blade length. In attendance were Dr Dan Smale and Dr Pippa Moore and 3 NFSD technical staff.

Thursday 7th September

Data collection at site 2 in Orkney. Four divers completed two distinct operations to collect in situ data on kelp abundance and percent cover at 2 different depths (10 and 5 m bcd). Sixteen 1 x m quadrats were sampled and 10 replicate canopy-forming plants were collected from each depth. Plants were returned to the laboratory and analysed to quantify stipe biomass, blade biomass, stipe length and blade length. In attendance were Dr Dan Smale and Dr Pippa Moore and 3 NFSD technical staff.

Thursday 14th September

Data collected from Orkney were collated, formatted and quality controlled. Initial analysis was conducted by Dr Dan Smale. Data were then passed to Prof Michael Burrows to inform ongoing modelling activities.

Friday 27th October

Due to logistics and weather constraints, sampling near the Isle of Gigha was not possible in August. NFSD divers conducted the remaining dive surveys at the pre-agreed sites using standardised methodology in late October. The South Cara and East Tarbert site was sampled at two depths (11.6 m and 5.6 m bcd). Sixteen 1 x m quadrats were sampled and 10 replicate canopy-forming plants were collected from each depth. Plants were returned to the laboratory and analysed to quantify stipe biomass, blade biomass, stipe length and blade length. The East Tarbert site was also dived, but no kelp was present. In attendance were five NFSD technical staff.

ANNEX C: SUBMISSION FROM A POTENTIAL APPLICANT FOR A SEAWEED HARVESTING LICENCE.

Downstream Value Creation

The figures below reflect a market assessment submitted by a private firm during the consultation phase of the current project, and are reproduced with their permission.

10 years into production, the one potential entrant (their figures, 2016) estimates total potential value at:

Component Class	Annual Sales Volume (kt)	Sales Revenue (£m pa)
Functional Poly-saccharides	14.2	228
Neutral Poly-saccharides	6.7	64
Anti-oxidants	0.9	44
Others (total)	8.1	16
Total	29.9	352

The above number is considered to be an average value for an optimistic sector or industry development – *at the extremes, the range is estimate to be anywhere from £200 – 500 m pa in terms of sales revenue.*

Value Creation Index (VCI)

A simple Value Creation Index has been developed – this shows the ratio of the potential Sales Revenue created by a particular end use to the input cost of a tonne of harvested wet seaweed. It can be seen that the most attractive Use Area of real scale for Scottish Seaweed is (High Value) Chemicals, and it should also be noted that, at a basic level, a VCI of < 1 implies a destruction of value.

End Use Area	Annual Revenue (£m)	Value Creation Index	Comments
Animal Feed or Fertiliser	55	4.2	Limits on dosage levels applied
Human Food	74	5.6	Would require significant shift in consumer behaviour
Horticulture	74	5.6	Market scale limited
(High Value) Chemicals	352	26.7	Alginate etc
Personal Care/Cosmetics	?	As above (Chemicals)?	High expected value but relatively small volume potential
Biofuel (Ethanol)	7.5	0.5	Methane product also – similar or lower value

It is expected that the chemical / pharmaceutical application is most likely given its potential for value addition, however a mix of end uses is likely to develop in practice, partly due to the nature and properties of individual seaweeds, the state of development and scale of the markets for end products, and the reality that not every company would want to, or be capable of, going into the highest value markets.