Mapping the intertidal seaweed resources of the Outer Hebrides

Scottish Association for Marine Science[1]

Hebridean Seaweed Company[2]

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Michael T. Burrows[1], Martin Macleod[2], Kyla Orr[1]

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1 Executive Summary

The Scottish Association for Marine Science (SAMS) and the Hebridean Seaweed Company (HSC) were commissioned by Scottish Enterprise and Highlands and Islands Enterprise in March 2010 to assess the intertidal seaweed resources of the Outer Hebrides: the rockweed *Ascophyllum nodosum*. The project was divided into two areas:

(1) Engagement and consultation with SEPA, SNH, Crown Estate and other key stakeholders involved in licensing seaweed harvesting in Scotland to ascertain the restriction and requirements for measuring seaweed stocks and sustainable harvest. The purpose of this engagement was to develop a robust field methodology agreed with key stakeholders.

(2) A mapping exercise to deliver a step-based approach to levels/availability of harvest, accounting for economies of scale and identifying opportunities and new areas for harvest justifying investment in infrastructure and equipment.

The agreed field methodology was used in shore surveys between April and October 2010 and combined with habitat modelling to deliver map-based estimates of the biomass of rockweed. The approach is flexible enough to allow estimates of biomass in other areas of Scotland with relatively little extra survey work.

Biomass estimates from this study, in 1000s of metric tonnes (t), are summarized here:

			Harvest scenarios			
	Total biomass		<3km from landing sites		25% annual harvest	
Island	All	>60 t/km	Current	Full	Current	Full
Barra	3.9	3.1	0.0	3.1	0.0	0.8
Harris	26.7	25.4	12.3	14.7	3.1	3.7
Lewis	69.0	67.9	33.1	37.7	8.3	9.4
North Uist	37.7	36.6	13.0	13.0	3.3	3.3
South Uist	31.6	30.4	2.2	28.7	0.6	7.2
West	1.4	1.3	0.1	0.1	0.0	0.0
Total	170.5	164.7	60.7	97.4	15.2	24.3

SAMS/HSC 2010 final estimate (All total, above) for the Outer Hebrides was170500t. This was close to the 1947 estimate of 123000t made by the Scottish Seaweed Research Association. 90% of rockweed biomass was in high yield harvestable areas (>60t/km). The largest percentage of the best estimate of total biomass was predicted to be found on Lewis (41%), followed by North Uist (22%), South Uist (19%) and Harris (16%), Barra having very little (2%).

Harvest scenarios were made on the basis of accessible resources, within 3km of landing sites. The present harvesting industry can access 60700 tonnes of *Ascophyllum*, 36% of the total (Current above). With a larger range of landing sites (Full above), this could rise to 97000t or 59% of the total available. For a sustainable harvest, areas should be left for at least four years between cutting events to allow regrowth. Faster recovery is possible if longer plants are left by harvesting (>25cm), at a cost of reduced harvests (50%). The sustainable annual harvest should be no more than 25% of the total accessible biomass: giving 15000t for the current industry, and 25000t if a larger network of landing sites were developed.

Stakeholders did not raise any specific issues with the proposed and adopted protocol. Where interested parties expressed an opinion, this was that full details of the methods used should be made available. Stakeholders also made their views known on the further development of intertidal seaweed harvesting in the Outer Hebrides. Opinions ranged from a desire for less regulatory interference in the harvest through to a strong need to protect natural habitats and species from potential damage. An accurate assessment was welcomed as a good first step for clear and rational management of the resource.

The methodology used is completely and directly applicable and scalable to a Scotland or UK-wide estimate of the biomass of *Ascophyllum*. The same principles and only relatively minor modification to the methods could also be used to make estimates for the biomass of other algae, especially the subtidal kelps (*Laminaria* species). Further surveys, information on the availability of rock habitats at given depths and on regional differences in water clarity would all be needed for robust estimation of biomass. Much of the additional information needed is already available: detailed bathymetry of the UK coastline from Seazone[1] and satellite information on ocean colour, a suitable proxy for clarity, from space agencies such as NASA[2].

2 Introduction

This project aimed to provide an assessment of the harvestable intertidal seaweed resources of the Outer Hebrides of Scotland, with a primary focus on knotted wrack, *Ascophyllum nodosum*. A widespread survey of the main potential and existing harvesting areas was done and the resulting data analysed using habitat mapping techniques to give an assessment of the total biomass of seaweed available. The sustainability of harvesting was estimated by combining the newly collected information on plant size, abundance and biomass with information on the capacity for the species to regenerate following cutting. The viability of existing and potential new areas for harvests was considered in regard to distance from landing points and transport to processing facilities. We begin this report with a review of the previous work on seaweed biomass assessment in Scotland in the late 1940s and 1950s, and present a short literature review on harvest-relevant aspects of the biology and ecology of Ascophyllum. We then outline our habitat modelling approach, largely based on a newly developed high-resolution models of wave exposure (Burrows et al. 2008), used here to deliver maps and area-based estimates of biomass.

[1] http://www.seazone.com
[2] http://disc.sci.gsfc.nasa.gov/giovanni

2.1 History – The legacy of Frank Walker and the Scottish Seaweed Research Association

A major survey of seaweed resources around Scotland, including the *Ascophyllum nodosum* of the Outer Hebrides was done by the Scottish Seaweed Research Association (SSRA, later Institute of Seaweed Research, ISR) in 1946-7 by a team led by Frank Walker. The estimates of the total biomass for *Ascophyllum nodosum* (Walker 1947a) and *Laminaria* (kelp) species (Walker 1953) made in this period have provided the most detailed information for managing and protecting this resource for the last 60 years. Subsequent reviews, such as the Minch Review (commissioned by SNH) (Bryan 1994) have all relied on these early studies. Walker's team used an approach based on site visits including surveys of the weight of plants per unit area and the extent of habitat area occupied by species. Detailed measurements from small scale (6" to 1 mile) maps were used to evaluate the area available in suitable areas, and combined with weight per unit area to give area-based biomass values. Until this study, the SSRA work has provided the most detailed and likely most accurate estimate of seaweed biomass in Scotland.

2.2 Ascophyllum nodosum *biology and ecology*

Ascophyllum nodosum is a slow growing, perennial brown seaweed that occupies the mid-littoral zone on rocky shores (Kelly et al. 2001). It typically grows on sheltered shores in temperate waters and is abundant on both the Irish and Scottish intertidal coastline (particularly abundant in the Outer Hebrides). This seaweed is widely distributed and is the most frequent macroalgae throughout the North Atlantic from northern Norway and the White Sea to Portugal in the Eastern Atlantic (Sharp 1987, Vasquez 1995).

The plant consists of a holdfast, a main shoot, base and lateral shoots, air bladders and reproductive receptacles (Fig. 1). The shoots arise from the holdfast and grow from their tips. Lateral vegetative shoots grow from pits along the main/primary shoot (Aberg 1996). Growth of plants is slowest in winter (Nov and Dec) and fastest in spring (April and May). Growth begins to decrease during the long periods of daily sunshine in summer (Stengel & Dring 1997). Growth rates are also significantly higher on the mid-shore, and plants grow slower on the lower and upper shores (Stengel & Dring 1997). Solar radiation is the factor that has the greatest influence on the growth of *Ascophyllum* on the upper and lower shore.

The shoots that arise from the holdfast produce one air bladder or vesicle float each year, usually in February (Aberg 1996). Primary shoots produce their first air bladder after 2 or more years after which one bladder is produced every year. It is thus possible to age *Ascophyllum* by counting the number of air bladders on the longest unbroken shoot (Stengel & Dring 1997). The species is long lived with an estimated life span of 50 to 60 years, and plants take approximately 5-8 years to reach their full size (Seip 1980, Aberg 1992). Plants on the upper shore are more susceptible to mortality due to breaking, and the age of plants increases progressively from the upper to lower shore (Stengel & Dring 1997).

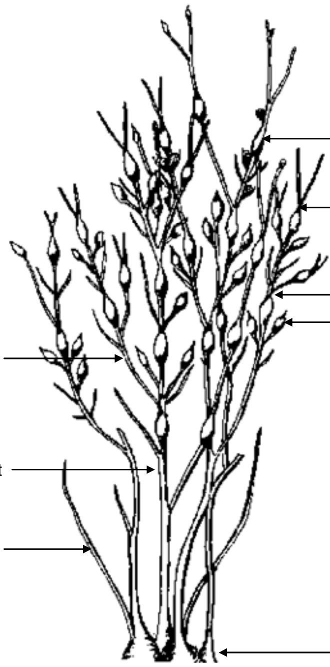

Fig 1. *Ascophyllum nodosum (Adapted from Sharp, 1987)*

Ascophyllum reproduces both sexually and asexually. Sexual reproduction is however very inefficient and in colonized areas vegetative reproduction from basal shoots is the most important form of propagation (Aberg 1996). Reproductive receptacles grow from the pits along the main shoot and have a life span of approximately 1 year. On the Swedish west coast receptacles first appear in June and reach their maximum size by the following year, after which they release their gametes into the water (Aberg 1996). In Nova Scotia gametes are reportedly released over a 1 month period in spring, usually April (Lazo & Chapman 1996)

Several environmental factors optimize biomass production; these include water depth, irradiance, water circulation, nutrient concentrations and the concentration of CO_2 and O_2 (Gao & McKinley 1994). Increased water flow, light and nutrient concentrations (inorganic N and P) all boost the rate of productivity. Seasonal variations in these parameters lead to seasonal variation in macroalgae productivity. The concentrations of nitrates and phosphates in temperate waters tend to be higher in winter and lower in summer (dependant on runoff). Faster water flow and improved circulation increase the uptake of nutrients, but very high currents can affect morphology of the plants. If the density of macroalgae is too high nutrients and light become limited and productivity declines. Population densities, which can be controlled by harvesting, need to be kept at an optimal level to enhance production (Gao & McKinley 1994).

2.3 Studies on the impacts of commercial harvesting

Ascophyllum nodosum has been harvested for decades from the coastlines of Ireland, Scotland (Outer Hebrides), Canada and Norway. The majority of studies conducted on the impacts of harvesting focus on the resource itself, rather than the effects it has on associated flora and fauna.

Factors that may affect the bed recovery and regeneration and well as associated biodiversity include; amount harvested, size of area harvested, the homogeneity of the harvest, equipment used, wave exposure and presence of grazers (Kelly et al. 2001).

2.3.1 *Ecological studies in Britain and Ireland*

The most recent study on the harvesting of *Ascophyllum nodosum* in Scotland was in the Outer Hebrides in 1994 (Tyler 1994). The study was done over a short period of time (July and August 1994) and aimed to investigate the recovery of *Ascophyllum* and its immediate ecosystem after harvesting. This was the first study on the ecological changes and recovery of *Ascophyllum* after harvesting in the Outer Hebrides. Cutting in the Outer Hebrides was done using a hand sickle and was carried out throughout the year around spring low tide. After cutting the *Ascophyllum* was left to regenerate for 3 – 5 years. The cutters at the time of writing were trained to leave enough of the plant for regeneration, but the cutters state that they cut as close to the rock as possible. The study focused on the effects of harvesting as it was actually practiced in Lewis and Harris, and did not involve any experimental cutting.

Three sites that had been harvested on known dates, and adjacent control sites that had not been harvested in twelve years, were surveyed. The percentage surface cover of *Ascophyllum*, density of associated species and substrate composition were determined. Tyler (1994) recognized that the regenerative capacity of the seaweed beds can be determined by considering mortality and recruitment in each area. This was done by recording the number of holdfast and *Ascophyllum* sporelings at harvested and unharvested sites.

Tyler (1994) found that at the most recently harvested site the numbers of *Ascophyllum* holdfast was significantly lower than at the control. This indicated that there was mortality of *Ascophyllum* immediately after harvesting. There was no significant difference in the number of holdfasts between the controls and those sites harvested several years ago, indicating a regenerative capacity of 3-5 years. The number of sporelings was higher at the most recently harvested site, possibly due to increased light and space (Tyler 1994).

The percentage cover of *Ascophyllum* was significantly lower in the cut area, while *Fucus vesiculosus* and *Ulva* cover were significantly higher in the cut area. It has been suggested that *F. vesiculosus* cannot compete with dense *Ascophyllum* cover. *Fucus* has been found to grow faster and replace *Ascophyllum* when it is cleared, while *Ascophyllum* grows slowly and has low recruitment levels (Kelly et al. 2001). Grazing pressure from periwinkles is thought to control the competitive dominance of ephemeral (short-lived) algae. An increase in ephemeral algae may lead to an increase in grazers (littorinids and other herbivores), which would then decrease with the establishment of the fucoid canopy (Lubchenco 1980, 1982, Chapman & Johnson 1990). The internodal length was significantly higher for *Ascophyllum* in the cut area indicating accelerated growth after cutting. This was attributed to greater light availability. Previous studies found that growth in areas sequentially harvested was usually higher in the first year than in successive years (Baardseth, 1955, in Kelly et al. 2001).

2.3.2 *Growth and recovery of Ascophyllum nodosum after harvesting*

Several studies have assessed the impact of harvesting on the growth, reproduction and survival of *Ascophyllum* plants. After a couple of early studies (Walker 1948, Baardseth 1955), the majority of this work was carried out in the 1980s and 1990s (Walker 1948, Seip 1980, Keser et al. 1981, Ang et al. 1993, Tyler 1994, Ang et al. 1996, Lazo & Chapman 1996, Kelly et al. 2001).

The optimum regeneration period for plants varied in each study and at each location, and was directly related to harvesting intensity (Seip 1980). Baardseth (1955) gave an optimum regrowth period of 5-6 years for maximum long-term yield in Ireland, and Tyler (1994) reported full recovery of *Ascophyllum* beds 3-5 years after harvesting. In Canada and Scotland a re-harvest interval of 3 or more years was generally used (Sharp 1987). There are however reports of delayed recovery (10-12 years) after extensive amounts of biomass have been harvested (Sharp & Pringle 1990, Davis et al. 2007). Repeated experimental cutting of *Ascophyllum* on an annual basis, leaving stumps of 15-30 cm, can also lead to reduced annual biomass (Sharp 1987).

Factors that can inhibit re-growth of *Ascophyllum* include lack of algal recruitment, reduced survival of existing plants, grazing by herbivores (Keser et al. 1981), inter-specific competition for space and resources and increase in wave exposure (Petraitis & Dudgeon 2004, Davis et al. 2007, Petraitis et al. 2009). Other factors that can influence the recovery of the community after cutting include seasonality, intensity of harvest, method of harvesting and its impact on reproductive structures, and the reproductive cycle of the plant (Vasquez 1995). Wave exposure has also been found to influence recovery of *Ascophyllum*, with mortality increasing from 20% on very sheltered shores to approximately 40% on exposed shores (Seip 1980). Keser et al. (1981) also found that regrowth of *Ascophyllum* was dependent on the age and size structure of the plants. Harvesting during the periods of highest reproductive activity can greatly reduce reproductive output of *Ascophyllum* (Sharp & Pringle 1990). However, as mentioned above, sexual reproduction by *Ascophyllum* is very inefficient, and recovery of the plants after harvesting largely depends on the amount of residual biomass (Sharp & Pringle 1990).

The amount of base vegetation left after cutting is an important factor in determining the regrowth period. For example, if plants were cut to 0.5% and 12% of their carrying capacity, the biomass after 3 years would be 23% and 70% respectively. The amount of biomass traditionally left after harvesting is approximately 2%, which corresponds to the stumps and shoots 10cm high (Seip 1980). Seip (1980) predicted that the yield of *Ascophyllum* could be increased by 40-70% percent by leaving behind a greater part of the biomass than is traditionally done, and the stock could be harvested twice as often. For example, if stocks were to be harvested every 2, 3 and 4 years, the base vegetation left for regrowth would need to 20-30%, 8-10% and 3-4% respectively (Seip 1980). If the rocks are scraped clear of holdfasts *Fucus* spp. may occupy the area for many years (3-12 years), or predation of plants will slow recovery (Seip 1980, Jenkins et al. 2004).

The earliest study of the regrowth and recovery of *Ascophyllum nodosum* and one of the most relevant was made by the Scottish Seaweed Research Association following the recovery of strips of cut plants over 2 years from 1946 to 1948. Plants were cut to leave different lengths for regrowth (Table 1, below). Yields after 2 years were greatest when 28cm (11") were left attached, suggesting that long-term yields would be highest and recovery faster if only 50% of the plants were cut. This however presents particular problems for hand cutting since it would require cutting across the thicker part of the plant.

Table 1. Recovery of *Ascophyllum nodosum* at the Skerry of Work, Orkney, from Walker (1948). Plants were cut in August 1946 in four 20 yard by 1 yard strips and recut in September 1947 and August 1948. Walker showed that leaving around 30cm of plant for regrowth was the most economical method over a 2 year period.

Strip	Length remaining (cm)	New plant growth after 2 years	As % of density before cutting	Wt left (kg/m^2)	Wt harvested (kg/m^2)	Available after 2y (kg/m^2)	Harvest in 2y (kg/m^2)
Before				13.0			
A	5.1	64%	40%	1.6	11.4	5.2	16.6
B	12.7	70%	48%	2.7	10.3	6.2	16.6
C	20.3	60%	83%	4.9	8.1	10.8	18.9
D	27.9	61%	104%	6.5	6.5	13.5	20.1

Harvesting has been shown to change the population structure of *Ascophyllum*. Unharvested populations typically have a bimodal structure (2 dominant population classes). After harvesting the population is reduced to being unimodal, as all the long fronds have been removed. After approximately 3 years the *Ascophyllum* plants begin to return to a bimodal population structure and thus plant length and modal structure have been suggested as good indicators for the state of recovery of the resource (Ang et al. 1993, 1996). Harvesting of *Ascophyllum* can also enhance growth, and this has been related to the increase in light availability, improved water flow and availability of nutrients (Sharp & Pringle 1990).

3 Stakeholder engagement

Engagement with stakeholders was aimed to determine the acceptability of the assessment method and to gauge opinions on any exploitation of the natural resources and the issues raised by the harvest. Stakeholders were contacted by letter (Appendix) and directly by phone or in person. Direct discussions were guided by a list of prepared questions, outlined here:

3.1 Key Issues

We approached the direct consultation with landowners as stakeholders by developing a discussion guide that aimed to address the key issues one by one. The guide ensured that all discussions had a common approach, but without restricting the consultee's response through prescription or closed questions. The responses were wide ranging and are summarised here:

1. Acceptable levels and management of harvesting

It was generally considered that management of the harvest needs an accepted management system in place that is based on sustainable principles, avoiding over harvesting of particular areas and without undue impact on other species, including for example brown trout that may use the seaweed beds as important habitats.

2. Regulation - the effectiveness of the existing and prior regulatory framework

Crown Estate granted leases for harvesting agreed tonnages in specific areas after consultation with relevant parties, and accepted royalty payments for harvested weed. The primary lease-holders before the Hebridean Seaweed Company were Kelco/Alginate Industries but the business declined with increasing overseas competition.

Some stakeholders felt that limits were unnecessary when local people were doing the harvesting, since a degree of ownership of the resource ensured that the harvesters faced the consequences of unsustainable cutting. Opposition was voiced to the involvement of the conservation agency, Scottish Natural Heritage, in the regulatory process as this might add delay to the granting of leases. It was felt that overall limits should be clearly stated, with local estates managing the licences.

3. Barriers and opportunities for growth in the seaweed industry

The size of the natural resource was seen as the ultimate limit to the growth of the industry. Designation of protected areas for conservation was also seen as limiting the harvest. Problems of access to and transport from remote areas, and onward transport of final products were seen as important. A role for government was seen for developing the necessary transport infrastructure. The renewable energy sector and anaerobic digestion is seen as a commercial opportunity for harvesters, although it was recognised that opportunities for higher value products from seaweed could be explored first. The market is seen as unreliable, while the distance to any processing facility appears to be a disincentive. Conditions and contracts for harvesters are thought to need improvement: contracts need to be more formally set out to give some degree of security of employment.

4. Potential routes for growing the industry

The limited upper size of the natural harvest requires that cultivation needs to be considered, with a limited commercial pilot. Quantification of the resource will help set upper limits for harvesting and thereby the commercial potential of the species. Access and manpower should be looked at also when investigating the potential for seaweed exploitation as these are important if there is to be large scale harvesting. Transport costs are a major issue and assistance should be sought to make these cheaper. Co-digestion with other waste might make more financial sense for obtaining fuel from seaweed.

5. Other harvestable seaweed species

Stakeholders had little knowledge of the regulations for harvesting other species, but recognised that quantification of the resource would be needed as a first step towards a sustainable harvest.

6. Cultivation of seaweed and implications

Marine cultivation of macroalgae was seen as a likely development, lacking a lot of the problems of freshwater- or land-based cultivation. It is based on proven technology in east Asia, but may have special issues in the Outer Hebrides including transport from remote cultivation sites and potential navigation problems around seaweed farms. Careful consideration should be given to the price set by the Crown Estate for leasing sites to avoid making seaweed cultivation uneconomical.

High value edible seaweed may be the most realistic target species, with Crown Estate regulation similar to that for mussel farms but with a supportive approach. Such farms may have a risk of theft from cultivation lines and additional security measures may be needed.

7. Other comments

Estate managers expressed a desire to be involved in any working groups established to develop and manage the harvest. It was felt that there should be more support for seaweed research for the Outer Hebrides if Highland and Islands Enterprise are to be involved in this sector.

3.2 Responses to the Consultation Letter and email

The responses to the consultation letter (see section 7.1) are given below. All responders wanted to see more details of the methodology adopted and the outcome of the survey: this Report in summary or in full.

3.2.1 *Text of an email from David Philip, Sustainability Manager, Crown Estate (19/5/2010)*

Michael and Martin,

I have just received your letter from our Managing Agents Bidwells regarding the mapping of seaweed resources in the Outer Hebrides. This is very much tied to an agreement The Crown Estate has with the Hebridean Seaweed Company to harvest (cut and carry away) seaweed *ex adverso* in Lewis and Harris.

I've circulated a copy of your letter to colleagues for comment. Their main comments are:

- *A. nodosum* ecad *mackaii* is a BAP species and priority species under the Convention on Biological Diversity. It's important as a creator of unusual habitat, and is found in quite a few locations around the Outer Hebrides. It is worth pointing out its presence as SNH will be concerned about it.
- I'd also suggest pressing for definition of phase 2, in which more empirical work on actual impacts could be done. There is often a lack of evidence with these things and it would help The Crown Estate if the evidence base is sound.
- The Crown Estate would require more detail and the unequivocal endorsement of SNH and other stakeholder interests of the mapping proposals

Bidwells will be able to quickly guide you over your planned areas of mapping, The Crown Estate land area ownership in specific locations (i.e. foreshore) and whether there are any existing and competing users of the seabed and foreshore in your proposed mapping areas.

A summary of your planned mapping and data gathering would be appreciated.

Clearly the results will influence the harvesting industry, therefore, very applicable to The Crown Estate. Sharing of this information will ensure The Crown Estate is fully kept up to date with the growing demands upon the resource, as well as the influence of harvesting on the wider marine environment.

We welcome your study and would be happy to assist with information, where we can, as the study will inform the sustainable exploitation of the resource.

We look forward to being kept informed of further development and results.

Best regards

David

3.2.2 *Text of a letter from Stuart Baird, SEPA (11/6/2010)*

Dear Dr Burrows

MAPPING OF THE SEAWEED RESOURCES OF THE OUTER HEBRIDES

I refer to your letter dated 5 May 2010 seeking SEPAJs comments on the proposed methodology for the above project which aims to re-assess the harvestable seaweed resources of the Outer Hebrides, this having last been undertaken in the 1940s.

I have asked for advice from my colleagues in SEPA's Marine Science section who have carried out a review of some of the available literature, details of which are provided at the end of this letter.

As you will no doubt be aware there have been a number of surveys carried out on seaweed harvesting, with a couple of main types; a very broadscale assessment with fairly sparse sampling effort, this is therefore likely to have relatively low confidence in the estimates of what constitutes a sustainable resource, the other is a more local scale assessment, with higher sampling effort, and should therefore have a higher confidence in sustainable yield estimates. Most surveys employ variations on a theme, but some don't fully explain what they've done, so it's not really possible to say there is one standard, recommended way to do it. Clearly the absence of an explanation of the methods is not helpful.

However, there is an Irish study from the mid-1990s that took the very practical approach of not just assessing the density of algal biomass present, but also its accessibility and the practicality of harvesting. If it's in a remote area with poor roads and road transport is to be utilised to move the seaweed from the point of harvesting to the factory then there is likely to be a high cost in upgrading the infrastructure to make it work. There is also the question of who owns access and any licensing issues. It would be sensible for any survey to include as much of this type of information as possible. SEPA does not hold any information on access or licensing issues. These practical aspects would of course be key to identifying what is actually available rather than theoretically available.

You should ensure that you do not collect the free-living variety *A. nodosum* va. *Mackaii*. This is a BAP species, which only grows in very sheltered areas of some sea lochs. It would be useful if you could give some sort of idea of the degree of confidence that you would have in your estimates, difficult as that may be.

Ascophyllum nodosum is the main intertidal fucoid alga for alginate production, but the quality of plants can vary for a variety of reasons. It's not clear, from the literature, how the quality of plants has been assessed in previous surveys. What is clear is that there seems to be a three year minimum recovery period after harvesting, with estimates of 3 to 6 years depending on the area looked at and the harvesting intensity. Even after recovery of biomass to pre-harvesting levels, the community structure is not the same and the area may not be as rich ecologically compared with an unharvested area. The density of *Ascophyllum* also seems to vary vertically on the shore throughout the bed, so you should ensure the location of your quadrats covered that aspect. Clearly the potential yield will be affected by the recovery period and this information on recovery period should be backed up by evidence. SEPA's primary concern would be to see that any harvesting is undertaken in a manner that is sustainable and does not therefore harm the ecosystem or affect the classification of the relevant waterbody under the Water Framework Directive.

You should be aware that there are areas of marine nature conservation interests around the coastline of the Western Isles which might necessitate additional precaution, for which I presume you will receive further information from Scottish Natural Heritage. SEPA would be interested in receiving a fuller account of your methods and would also welcome the final report.

Please feel free to contact me or Dr Scanlan should you wish to discuss this matter further.

Yours sincerely

Stuart Baird

Unit Manager

SEPA Western Isles Office

Literature reviewed:

Fuller, Cleator and Irvine, 1996. L.Sunart & L.Teacuis littoral biotope survey and seaweed resource assessment.

Hession,C., Guiry,M., McGarvey,S. & Joyce,D. 1998. Mapping and assessment of the seaweed resources (Ascophyllum & Laminaria spp) off the west coast of Ireland.

Wilkinson, M. 1995. Information review on the impact of kelp harvesting.

3.2.3 *Text of an email from Roddy MacMinn, Scottish Natural Heritage (20/5/2010)*

Dear Dr Burrows

cc Martin & Malcolm HSWC

Thank you for your letter regarding your proposed study of the Ascophyllum resource of the Outer Hebrides (in partnership with the Hebridean Seaweed Company). I'd appreciate it if you could forward me the further details mentioned in that letter (outlining the proposed methodology) for our consideration*.

It's good to see work like this being undertaken, and we would be fully supportive of any study that can add to our understanding on the sustainability of seaweed harvesting in the Outer Hebrides,

with best wishes

Roddy

*The survey methodology did not change from that outlined in the Consultation Letter (section 7.1) as having been adopted since the beginning of the survey in late April. SNH indicated subsequently that, despite the lack of further consultation on survey methods, they were happy with the scope of the study. In SNH's view, the assessment should also ideally have shown ecosystem as well as *Ascophyllum* recovery and also have considered potential impacts on designated sites and European Protected Species. We felt that such additional studies would have needed a much longer term study or targeted surveys of previously harvested areas, beyond the scope of this study.

3.2.4 *Responses to the Consultation Letter from other stakeholders*

Local landowners expressed a variety of opinions about the prospect of seaweed harvesting. Some did not want to see neighbouring coastlines as the focus of commercial harvesting efforts and were concerned that such harvesting would have a negative impact on marine life. Stakeholders wanted to be assured that the relevant regulatory agencies were fully involved in any plans to harvest weed, as well as all of their tenants. And that existing protection measures such as Special Protected Areas for birds were fully respected and considered.

Other local business owners were less concerned and welcomed the prospect of the development of any projects that could create long term employment in the Outer Hebrides.

4 Available seaweed resource

HSC and SAMS conducted a survey of the intertidal seaweed *Ascophyllum nodosum* along the east and west coasts of the Outer Hebrides between May and September 2010, mainly in sea lochs and other wave sheltered areas where the species predominates. Rock shores were accessed by boat over a period of 4h each day around the time of low water. At each shore, seaweed was completely removed from small areas (0.25m^2) of rock at levels on the shore spanning the vertical distribution of *Ascophyllum*. Plants were measured and weighed and the location of each area was recorded using a GPS logger. SAMS developed the detailed methods of data recording and the design of the seaweed survey in terms of the desirable number of sites per sea loch and distance along the coastline.

Statistical analysis and modelling of the data was done at SAMS to detect trends in biomass and the likelihood of presence of *Ascophyllum* and amount of habitat occupied, particularly with respect to the degree of wave exposure at each site. These trends were used to make predictions for all parts of the coastline of the Outer Hebrides.

4.1 Methodology for assessing coastal intertidal seaweed biomass

4.1.1 *Survey design*

The survey aimed to assess the size and density (kg/m^2) of *Ascophyllum* plants across the coasts of the Outer Hebrides. To do this, we planned site visits to most of the sheltered coastlines of the area. These sheltered areas are generally in sea lochs and we used these lochs as the basis for the plan for spreading survey effort across the whole area. The protocol below was designed to allow for 2 to 3 site visits per low tide period, defined as the time from 2 hours before to 2 hours after low tide, and a modest travel time between each site by boat. The number of sites per sea loch chosen was 2 to 6 depending on the size of the loch, with the number of days per loch emerging as a result. Our initial estimates of the distribution effort among areas are given in Table 2. Choice of sampling sites was guided by Mike Burrows' wave fetch index (background IP, Burrows et al. 2008). Previous surveys by SAMS in the Outer Hebrides in 2004 and around Scotland over the past decade (2002-2010) have shown that *Ascophyllum* does not occur on wave-exposed shores and such areas can be excluded from the surveys. SAMS data from wave-exposed shores in the Outer Hebrides in 2004 was combined the data collected in this study to establish how far *Ascophyllum* extended into more wave-exposed habitats.

Table 2. Sampling areas with projected and actual number of days and sampling sites per area.

Islands	Loch / Area	Plannned days for sampling	Planned Sites	Surveyed	Dates
Lewis & Harris (E. Coast)	Stornoway / Armish Point	1	2	3	13/04/2010
	Grimishader/Leurbost	1	2	2	12/04/2010
	Erisort	2	4	2	21/05/2010
				2	10/08/2010
	Gravir	1	2	2	12/08/2010
	Shell	2	4	2	31/08/2010
	Seaforth	2	4	2	01/09/2010
	Finsbay, Geocrab	1	2	2	09/08/2010
	Scalpay	1	2	1	11/09/2010
	East Loch Tarbert	1	2	2	09/09/2010
	Golden Road	1	2	1	10/09/2010
Lewis & Harris (W. Coast)	Bemera (E & W Loch Roag)	3	6	2	15/04/2010
				2	16/04/2010
	Loch Reisort	1	2	3	14/04/2010
	W. Loch Tarbert (Amhainn Suidhe)	1	2	2	09/09/2010
N & S Uist, Benbecula, Eriskay, Barra	Loch Maddy	4	8	3	17/05/2010
				1	18/05/2010
				2	19/05/2010
				2	20/05/2010
	Eiport	2	4	2	26/05/2010
	Grimsay	1	2	2	27/05/2010
	Carnan	1	2	2	28/05/2010
	Skiport	1	2	1	21/09/2010
	Aynort	1	2	2	21/09/2010
	Loch Boisdale	2	4	4	22/09/2010
	Eriskay	1	2	1	24/09/2010
	Barra	1	2	2	23/09/2010
Total		**32**	**64**	**54**	

4.1.2 *Site sampling protocol*

The following sampling protocol[3] for intertidal *Ascophyllum* was used at each site.

1. Predicted vertical heights above Chart Datum of the water level were calculated each day using tidal predictions for the survey locality and adjusted for barometric pressure variation (10cm for 10mbar). At the top of the shore, above the highest level of intertidal seaweeds, a base station was identified for deployment of a theodolite. The theodolite was used to estimate vertical distance relative

[3] A full assessment of Health and Safety issues was carried out in preparation for the site visits. SAMS requires a Safe System of Work and Risk Assessment to be carried out for all fieldwork and this was prepared before the survey. Daily checks included: (a) boat damage, (b) adequate fuel supply, (c) safety equipment (life jacket, flares etc), (d) VHF radio and a report to the coastguard with the location of the day's work.

to the reference water level at the start of the survey, and the predicted water level above Chart Datum at this time added to these vertical distances to give tidal height for survey points.

2. The profile of the shore from Mean High Water Springs to the starting reference water level was established using the theodolite and measuring pole to determine the tidal height of the rock surface at intervals along a tape measure laid out down the shore. We aimed to collect at least 10 vertical points for the profile.

3. The vertical heights of the upper and lower limits of *Ascophyllum* were collected in the same way using the theodolite and measuring pole. Five locations were chosen within 10m of the transect line, and the heights of the lowest and highest *Ascophyllum* plants were recorded.

4. Three levels were identified within the vertical zone of *Ascophyllum*, corresponding to the mid point of the zone and levels 0.5m above and below this mid level.

5. Four 0.5m by 0.5m square frames (area $0.25m^2$, henceforth termed as **quadrats**) were placed randomly along a horizontal line perpendicular to the shore profile tape within 3m of the tape at each sample level, making a total of 12 quadrats per site. In each quadrat:

a. Four plants were selected at random and the length of the longest frond measured.

b. All plants with holdfasts within the quadrat were removed by cutting to within 3cm of the base. This will leave enough material for the plants to regenerate. Most of these plants were *Ascophyllum* at the selected survey sites. Plants were sorted into species and put into numbered mesh bags for later weighing. Where necessary, bags of collected weed were immersed in seawater for some time to ensure a constant water content and so avoid bias due to differential drying in air through the period of emersion.

6. All data were recorded on waterproof pre-printed datasheets and entered into computer files after the surveys for appropriate analysis using GIS and other relevant software. Example survey sheets are given in the Appendix (section 7.2).

4.2 Developing a harvest

The current and future development of the harvest of the natural *Ascophyllum* resource in the Outer Hebrides was considered in relation to where the plants can be landed and transported to sites for processing and further use. Locations of current landing sites and locations of potential landing sites were collated during the study. Cut weed can only be towed by sea for a maximum 3km, limiting the area from which *Ascophyllum* can be harvested. This approach was used to assess the harvestable biomass. Given the requirement for a 3-5 year fallow period, the biomass of *Ascophyllum* within 3km radius of landing sites was divided by 4 to give the likely sustainable annual harvest.

Fig. 2. *Survey methods. The image shows the theodolite at the top of the shore and the tape marking the transect line. Martin Macleod is weighing* Ascophyllum *from a 0.25m^2 quadrat. Loch Resort, 14/4/2010.*

4.3 Mapping methodology

4.3.1 *Overview*

Studies at SAMS (Burrows et al. 2008) and elsewhere (Lewis 1964) have showed that wave exposure is a good predictor of *Ascophyllum* biomass. We used maps of a pre-existing index of wave exposure (Burrows et al. 2008) based on the publicly available GSHHS (Global Self-consistent, Hierarchical, High-resolution Shoreline) dataset (NOAA 2007) to establish the extent of suitable

habitat for *Ascophyllum* along the coastline of the Outer Hebrides. The wave exposure index is based on summed wave fetch, the distance to the nearest land in all directions open to the sea around a specified point. Geo-located sample data from the SAMS/HSC survey were spatially referenced with wave fetch for the nearest 200m grid cell in the wave fetch model. An example wave fetch map for Loch Maddy (left) shows wave sheltered areas by blue dots, with wave exposed areas shown in yellow. We used a two-stage regression technique to build a statistical model that firstly related *Ascophyllum* presence, and then plant weight and length to wave fetch and shore level. This was designed to allow for local or loch-scale variation in responses to similar environmental conditions if such variation were detected. The first stage model predicts the likelihood of presence of *Ascophyllum* plants for a given area, and the second model predicts the size and weight of plants in areas where the species was likely to be found.

Where relationships with environmental variables and among regions were statistically significant ($P<0.05$), these relationships were combined with the maps of wave fetch to produce estimates of *Ascophyllum* likely presence, plant size and weight at 200m intervals along the coastline. To estimate the total biomass of seaweed in a surveyed area we extracted the area of the intertidal zone from on-site observations of the width of the intertidal and the *Ascophyllum* zone, multiplied by the length of the rocky shoreline in the area. The predictive model gave the biomass in kg as a product of the estimated area covered by *Ascophyllum* and the predicted average weight of *Ascophyllum* per unit area of rocky habitat in the locality.

4.4 Comparison with original methods

This approach was mostly consistent with the previous surveys in the 1940s, with only minor differences in the survey methods for assessing seaweed densities and mapping resources. Walker's team weighed only the parts of plants falling within the quadrat (the measuring square), irrespective of whether the plants holdfasts originated in the quadrat. We (SAMS/HSC) included only those whole plants whose holdfasts were located in the quadrats.

Walker and his colleagues used a more detailed mapping process, using intertidal outlines traced from 6" to 1 mile (1:10560) to give the area of the intertidal rock available for seaweeds. Our approach and the resources available for our study did not allow for the level of detail. Digital sources for such areas do exist in Ordnance Survey and Hydrographic Office databases. Our estimates were based on lengths of coastline available from publicly available datasets (OS OpenData Land-Form PANORAMA), divided among the relative proportions of suitable habitat in appropriate wave exposure and rock conditions. Geographical Information System (GIS) software made such calculations relatively rapid in this latest survey.

Occasionally sometimes apparently arbitrary decisions were made in the early surveys. The acreage measured in Loch Maddy was doubled because the large boulders comprising the shoreline were thought to offer twice the area for attachment of plants (Walker & McLean Smith 1945) and thereby to support double the biomass. While substratum type and complexity may have an effect on the supportable biomass of *Ascophyllum* we did not attempt to account for such unquantified effects.

4.5 Survey results

Fifty five sites were surveyed in the Outer Hebrides between April and September 2010, with *Ascophyllum nodosum* plants weighed and measured in a total of 660 quadrats. Basic frequency distributions and trends with wave fetch and among the lochs, islands and coasts were quantified in exploratory analyses designed to inform the construction of the models used for final biomass estimation.

4.5.1 *Quantities of Ascophyllum in quadrats and at survey sites*

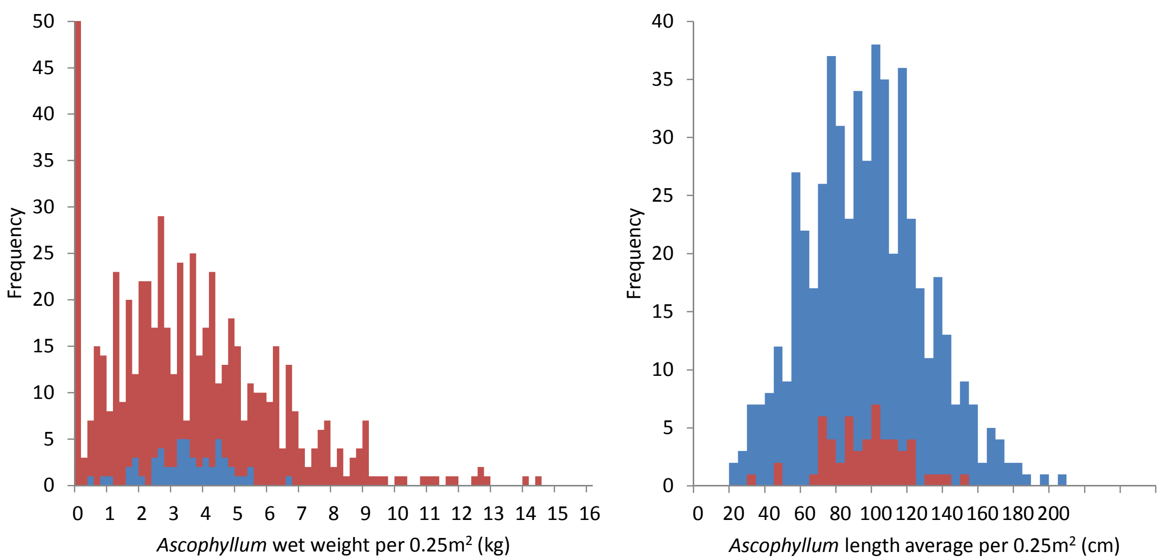

Fig. 3. *Frequency distributions of measures of wet weight and average length of* Ascophyllum nodosum *plants per 0.25m^2 quadrats. Average values per site are shown as blue bars for wet weight and red bars for length of plants. 109 quadrats had no* Ascophyllum*.*

Of the 660 quadrats recorded, 17% (n=109) had no *Ascophyllum* and the remaining 83% had up to 16kg in wet weight of plants (Fig. 3), with an average of 3.31kg and a standard deviation of 2.85kg, equivalent to 13.23 and 11.38 per m^2 respectively (or 24lbs per square yard). The average length of plants in each quadrat ranged from 20 to 200cm, with an average of 92cm and a standard deviation of 33cm.

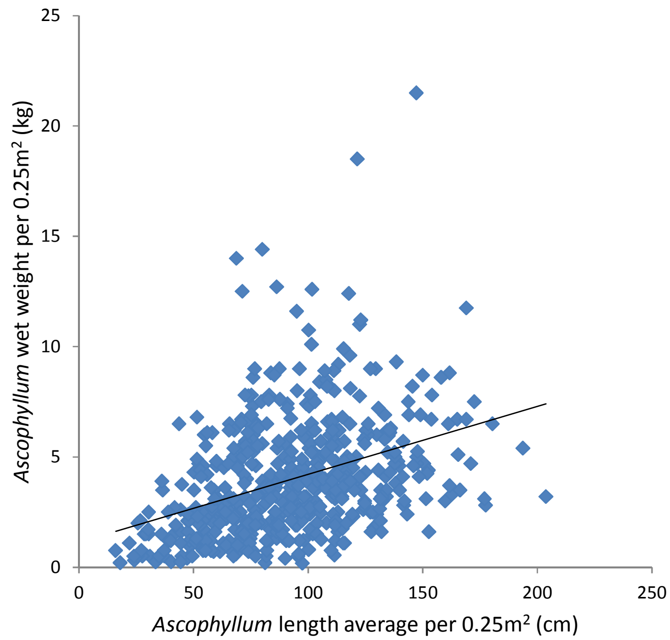

Fig. 4. *The relationship between wet weight and average length for* Ascophyllum nodosum *plants per 0.25m^2 quadrats.*

Wet weight per quadrat and average plant length were loosely correlated (r=0.378) with longer plants associated with greater yields (Fig. 4).

4.5.2 *Presence and absence of Ascophyllum versus wave exposure*

A major requirement of the modelling method is to establish the likelihood of finding the target species as a function of the environmental conditions considered. This form of analysis needs a good quantity of data from areas where the species is not found as well as where it is likely to be abundant. Because the survey effort in this study was focussed on estimating biomass in areas likely to yield a significant harvest, therefore, we combined the data with another set collected using the same methods from sites in the Outer Hebrides over a greater range of wave exposures in August 2004.

We modelled the likelihood of presence of *Ascophyllum* at a site defined as at least some plant material found in at least one quadrat (0.25m^2 n=8 per site in 2004 and n=12 per site in 2010) and per quadrat. This was done using binomial logistic regression, with data for per-site presence coded as 0 or 1 for absence or presence, and using the proportion of quadrats at a site with non-zero *Ascophyllum* for the likelihood per-quadrat regression. Over 90% of sites with a log10 wave fetch km value less than 1 (10km) were predicted to have *Ascophyllum nodosum* present (Fig. 5). *Ascophyllum nodosum* was recorded at only a single site (Smeircleit in at the southern tip of South Uist) with a logarithm to base 10 wave fetch value of greater than 2 (equivalent to a summed fetch distance of 100km over sixteen 22.5° compass angle sectors). The actual wave exposure at this site is much less than the model indicated, with submerged offshore skerries not resolved as coast in the wave-fetch model providing a good deal of protection from the incoming waves to the west of the site.

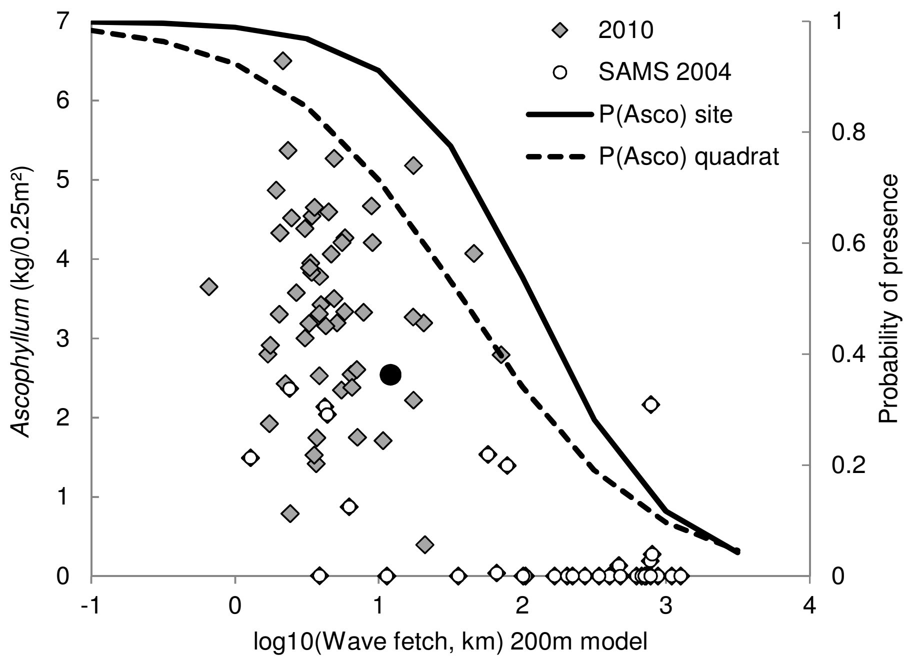

Fig. 5. *The relationship between average wet weight of* Ascophyllum nodosum *plants in 0.25m^2 quadrats and wave exposure, expressed as the logarithm to base 10 of total wave fetch in km. Weight of plants is shown against the left-hand axis and the probabilities of presence of* Ascophyllum *at sites (solid line) and in each quadrat (dashed line) are plotted against the right hand axis.*

4.5.3 *Vertical and horizontal extent of Ascophyllum beds*

The total quantity of *Ascophyllum* at a site is completely dependent on the extent of the shore occupied by the species. Our survey method was designed to capture this as accurately as possible, giving estimates of the heights of the lower and upper limits of the species and thus the vertical range. By determining the profile of the shore at each survey site we obtained the horizontal extent of the *Ascophyllum* plants both directly by measuring along the survey tape, and indirectly by getting the slope of the shore and the vertical range.

Vertical range decreased sharply from around 1.8m in wave shelter to less than 0.5m in the most wave exposed environments (Fig. 6), and this relationship was used as part of the model for predicting horizontal extent of *Ascophyllum* beds. On average vertical range was 1.68m, the lower limit being 0.93m above Chart Datum (CD) and the upper limit 2.57m above CD. The average upper limit was 0.82m below average Mean High Water of Neap tides (MHWN, 3.39m) and 0.04m below Mean Tide Level (MTL, 2.61m). The lower limit was, again on average, 0.28m above Mean Low Water of Spring tides (MLWS, 0.65m).

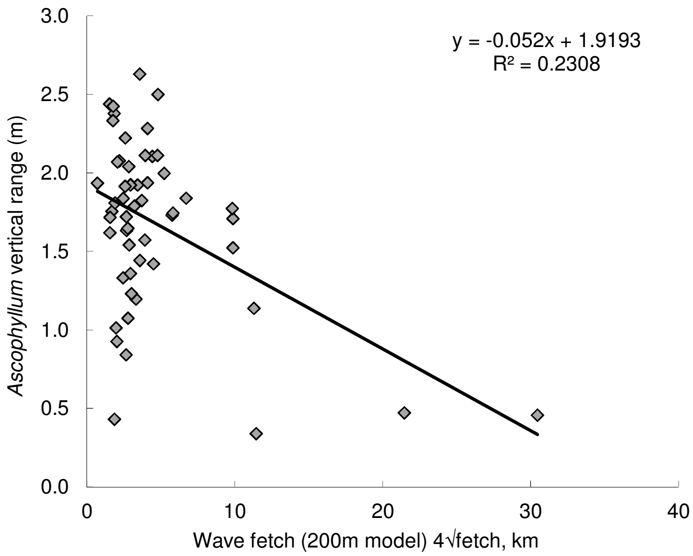

Fig. 6. *The relationship between* Ascophyllum *vertical range and wave exposure.*

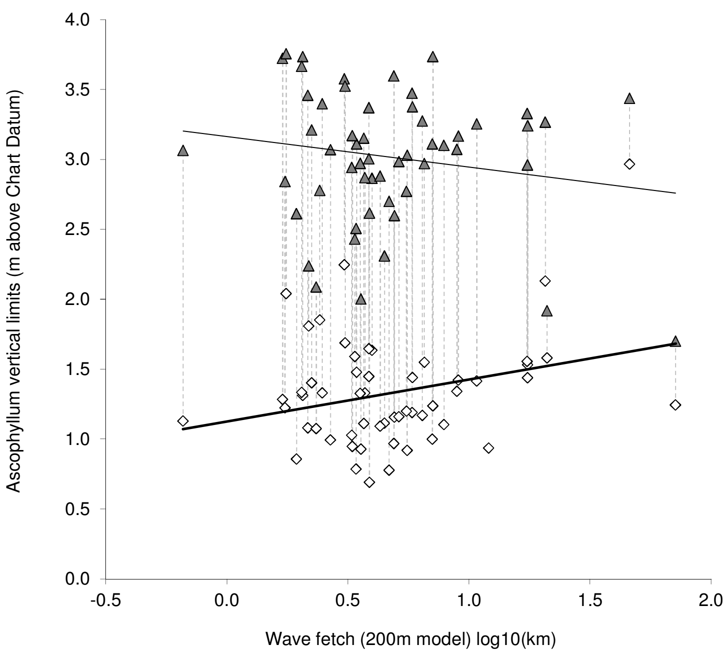

Fig. 7. Ascophyllum *upper and lower limits versus wave exposure. Upper limits are shown as closed triangles and lower limits as open diamonds.*

Vertical range and upper and lower limits were quite variable, with only vague (statistically non-significant, $P>0.05$) downward and upward trends with wave exposure (Fig. 7) despite the narrowing of the range with increased wave fetch. Narrow vertical bands of *Ascophyllum* were also occasionally seen in wave shelter. At the head of Loch Seaforth, for example, a very narrow (0.4-0.8m) band of *Ascophyllum* was seen around mid shore (1.6-2.4m above CD).

4.5.4 *Geographical patterns*

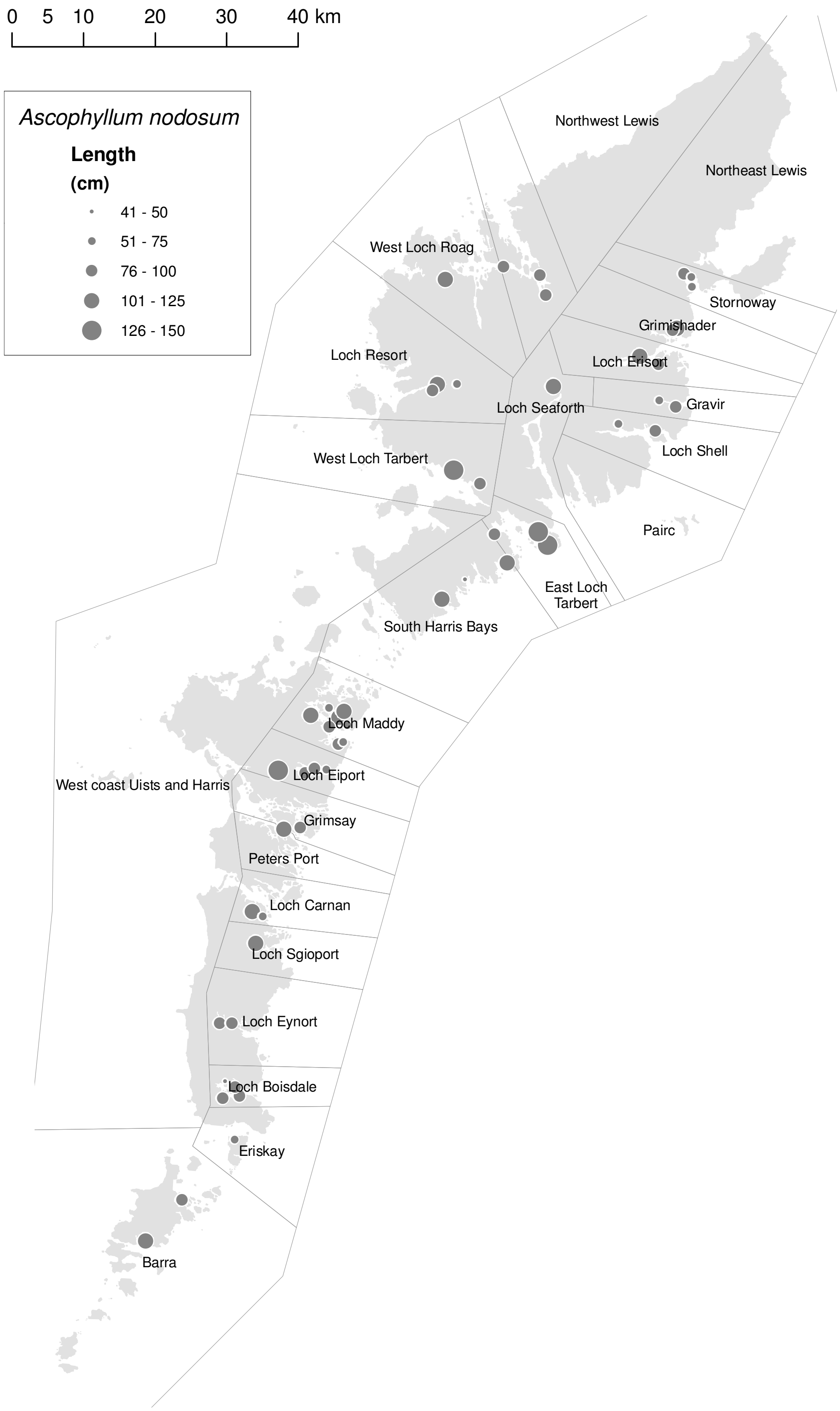

Fig. 8.A. *Distributions of average length of* Ascophyllum nodosum *plants in the Outer Hebrides.*

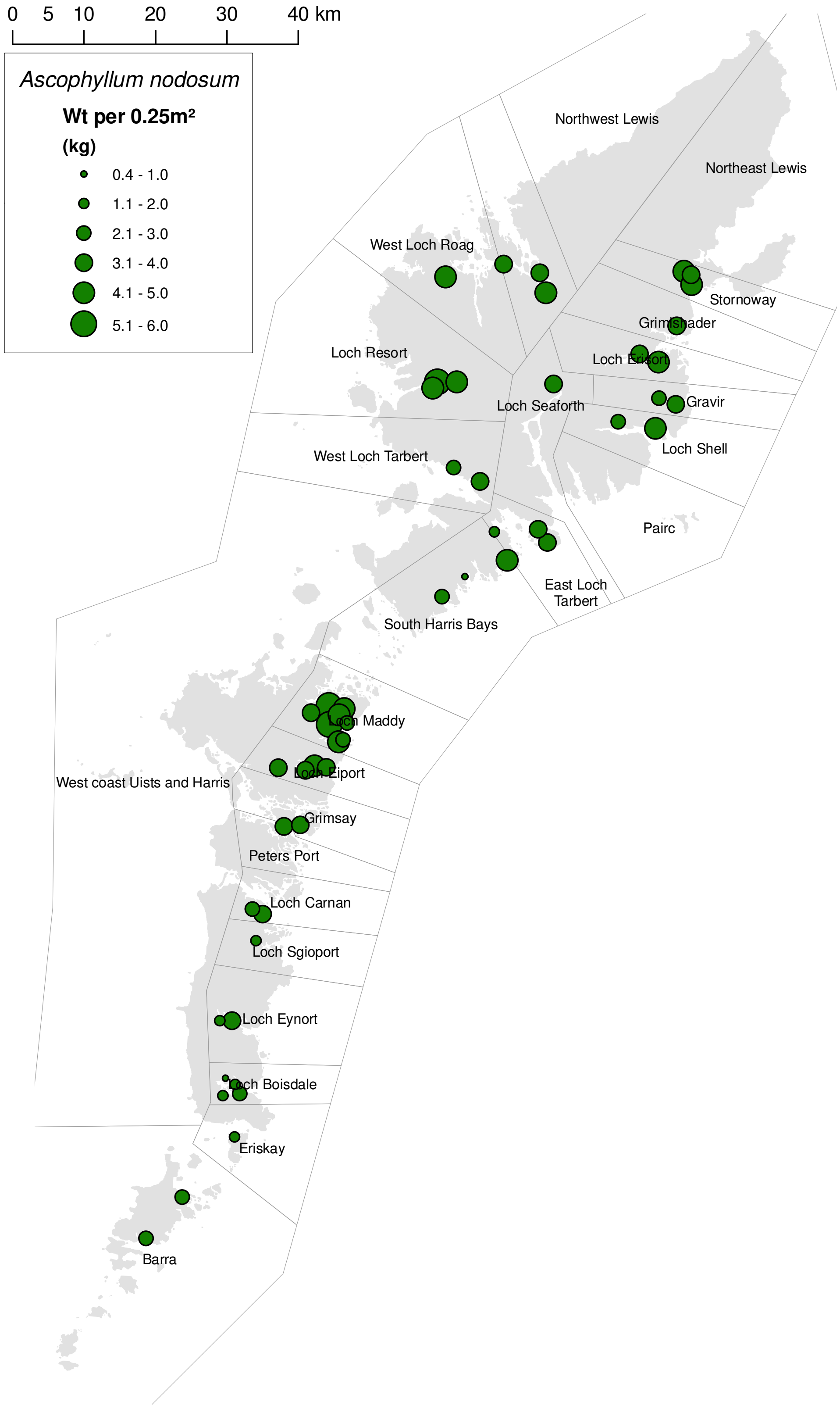

Fig. 8.B *Distributions of average wet weight (kg per 0.25m^2) of* Ascophyllum nodosum *plants in the Outer Hebrides.*

In geographical terms, average weights of *Ascophyllum* per quadrat varied among the different lochs and regions (Fig. 8, left). Yields per 0.25m^2 were lower in South Uist, Eriskay and Barra than in North Uist, Harris and Lewis. This trend can be seen clearly in plots of yields with latitude and longitude (Fig. 9). Although some of this variation may be due to differences in wave exposure of sites selected in 2004 and 2010, the trends persist when 2010 data is considered alone.

Average lengths of plants at each site showed no trends with latitude or longitude, but did show a decline in plant size with wave exposure from around 100cm in wave shelter to around 70cm at the most wave-exposed sites surveyed (Fig. 10).

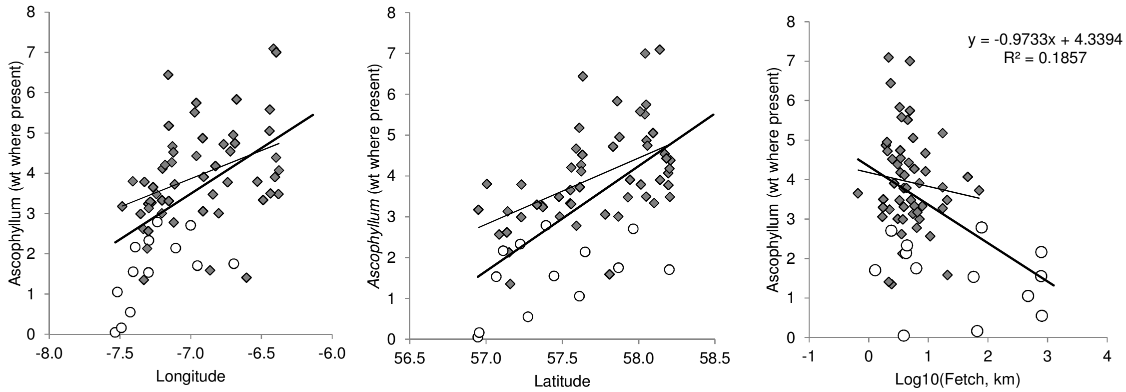

Fig. 9. *Geographical and habitat-specific patterns of* Ascophyllum *density (kg per 0.25m^2) in the Outer Hebrides. Solid triangles show data collected in summer 2010 and open circles from summer 2004. Thick lines show linear regressions fitted through all the data, while thin lines show regressions for 2010 data only.*

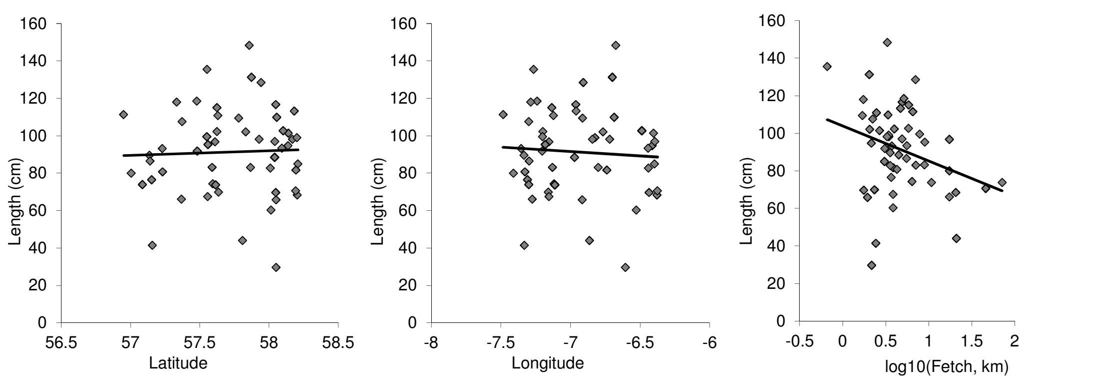

Fig. 10. *Geographical and habitat-specific patterns of average length of* Ascophyllum *plants (cm) in the Outer Hebrides. Symbols show data collected in summer 2010 and lines show linear regressions fitted to the data.*

4.5.5 *Statistical analysis of trends*

A summary of the statistical analyses of the patterns in plant yield and size, as well as the vertical extent of the occupied intertidal, is given in Table 3. Significant relationships used in model estimation of total *Ascophyllum* biomass are detailed in section 4.6 and shown in Table 4.

Trends were described by fitting the best regression models to the data. 'Best' models were identified as those with the best balance between the goodness of fit of the model to the data, measured by summed deviance or residual sum of squared deviations, and the number of parameters in the model. We used Akaike's Information Criterion (AIC) as the metric to judge models by (see for example Burnham & Anderson 2002), a measure that combines goodness of fit with a penalty for increasing numbers of parameters in complex models. Models with each combination of predictor variables (fetch, slope, latitude and longitude) and interactions were tested. Statistically non-significant terms were removed from the model with the lowest AIC value to give the final model, comprised of the terms shown in Table 3. Model parameters and their standard errors are given in Table 4.

Wave fetch values were transformed to fourth-root values in analyses. Presence of *Ascophyllum* was modelled using binomial logistic regression, while weight of plants, average length and vertical range were modelled using linear regression. All tests were done using the R software package (R Development Core Team 2010).

Table 3. Summary of statistical tests and indication of the direction of trends. Asterisks show the levels of statistical significance: ***, P<0.001; **, 0.01>P>0.001; *, 0.05>P>0.01; ns, P>0.05.

Response	Wave fetch	Slope	Latitude	Longitude	Fetch by Latitude	Use in Prediction
(2004 and 2010 data, n=86 sites)						
Presence of *Ascophyllum*	*** (-ve)	-	ns	ns	ns	**Yes**
Ascophyllum wet weight per 0.25m² (kg)						
average per quadrat where present	** (-ve)	-	*** (+ve)	ns	ns	**Yes**
average per site	** (-ve)	-	*** (+ve)	ns	** (-ve)	No
(2010 data only, n=54 sites)						
Ascophyllum wet weight per 0.25m² (kg)						
average per quadrat where present	Ns	ns	*** (+ve)	ns	ns	**Yes**
average per site	Ns	ns	*** (+ve)	ns	ns	No
Vertical range (m)	** (-ve)	ns	ns	ns	ns	**Yes**
Average length of plants (cm)	* (-ve)	ns	ns	ns	ns	No

Table 4. Parameter values used in model estimation of *Ascophyllum* populations from regression analyses. Values show parameter estimates (with standard errors in brackets).

Response	Intercept		Wave fetch ($\sqrt[4]{km}$)		Latitude (°)		Fetch by Latitude	
(2004 and 2010 data)								
Presence of *Ascophyllum*	4.5072	(0.799)	-1.233	(0.248)				
Ascophyllum wet weight per 0.25m² (kg)								
average per quadrat where present (1)	-90.88	(23.60)	-0.455	(0.166)	1.650	(0.408)		
average per site	-125.87	(36.63)	34.27	(11.99)	2.254	(0.635)	-0.609	(0.21)
(2010 data only)								
Ascophyllum wet weight per 0.25m² (kg)								
average per quadrat where present (2)	-82.18	(23.74)			1.492	(0.411)		
average per site	-92.25	23.523			1.655	(0.408)		
Vertical range (m)	2.625	(0.290)	-0.627	(0.187)				
Average length of plants (cm)	120.0	(13.22)	-19.0	(8.53)				

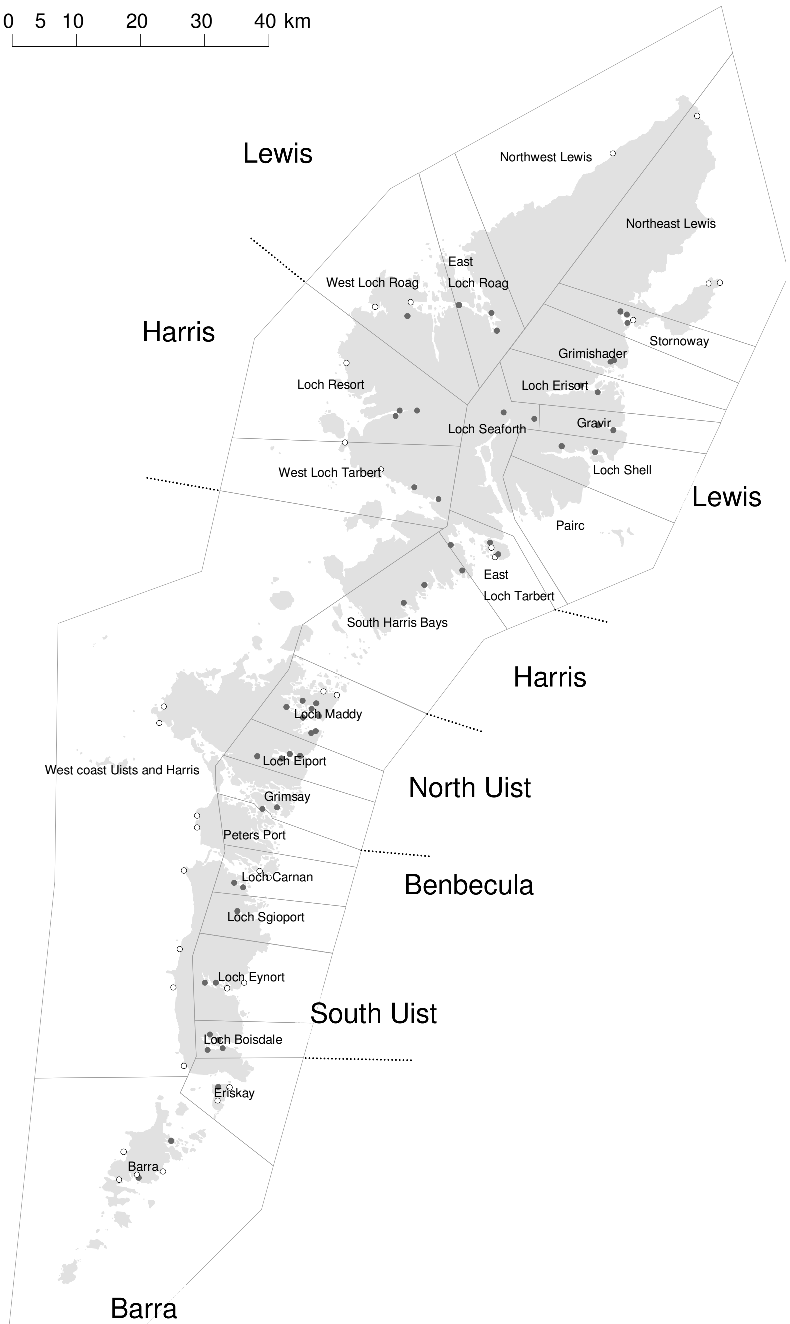

Fig. 11. *Subregions for* Ascophyllum *biomass reports. Survey sites visited in summer 2010 are shown as solid circles and sites surveyed by SAMS in 2004 are shown as open circles. Note: the base map does not resolve all upper branches of sea lochs – sites apparently on land are in such locations.*

4.6 Area-based estimates of seaweed resources

The Outer Hebrides were divided into 25 subregions for estimation and reporting *Ascophyllum* biomass and habitat extent (Fig. 11). The total length of the coastline within each of these subregions was obtained from the Ordnance Survey 1:50000 coastline dataset (OS OpenData Land-Form PANORAMA). This length was used as the basis for calculating the total area occupied by

Ascophyllum and to scale per km biomass estimates up to the whole subregion. Shores shown as dominated by entirely by sand and mud were deemed as being unsuitable for *Ascophyllum*. We used the Defra Intertidal Substrate Foreshore (England and Scotland)[4] from the UK Coastal and Marine Resource Atlas to classify each wave fetch model grid node as suitable or unsuitable for *Ascophyllum*.

4.6.1 *Maps: Local point estimates of Ascophyllum biomass*

Biomass estimates per unit length of shoreline (kg per m, equivalent to tonnes/km) were generated for each grid node in the 200m-scale wave fetch model. Every node had unique latitude, longitude and wave fetch value and these were used to generate an estimate of biomass in kg per m of shoreline using the following:

$$P_{Asco} = \frac{e^{a+b.F}}{1+e^{a+b.F}} \quad \text{(equation 1)}$$

where P_{Asco} is the probability of *Ascophyllum* presence in a quadrat, *F* is wave fetch (fourth root km), and *a* and *b* are regression parameters for *Ascophyllum* presence from Table 4. Vertical range was predicted as:

$$V_{Range} = a + b.F \qquad \text{(equation 2)}$$

where V_{Range} is the vertical range of *Ascophyllum* in metres and *a* and *b* are regression parameters for vertical range from Table 4. Horizontal range of *Ascophyllum* was obtained from:

$$H_{Range} = V_{Range} \ / \ Slope \quad \text{(equation 3)}$$

where H_{Range} is the horizontal range. Slope did not show any trends across the study region, so an average value from shore profiles was used (0.1714, the ratio of horizontal to vertical extent of the shore).

The width of the *Ascophyllum* bed was estimated as:

$$W = \sqrt{V_{Range}^2 + H_{Range}^2} \quad \text{(equation 4)}$$

The weight per unit area (kg/m^2) of *Ascophyllum*, M_{Asco}, in areas where the plant was present was estimated as either:

$$M_{Asco} = a + b.F + c.Lat \quad \text{(equation 5),}$$

when using 2004 and 2010 data combined, or

$$M_{Asco} = a + c.Lat \quad \text{(equation 6),}$$

when using 2010 data only, where *Lat* is the latitude of the grid node.

Estimated yield of Ascophyllum per km for each grid node was obtained as:

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4 (http://www.magic.gov.uk/datadoc/metadata.asp?datasetname=Intertidal%20Substrate%20Foreshore%20%28England%20and%20Scotland%29)

$$Y_{Asco} = P_{Asco} \, . \, W \, . \, M_{Asco} \quad \text{(equation 7)}$$

the product of the probability of presence, the width of the *Ascophyllum* bed and the weight of plants per unit area over the whole bed.

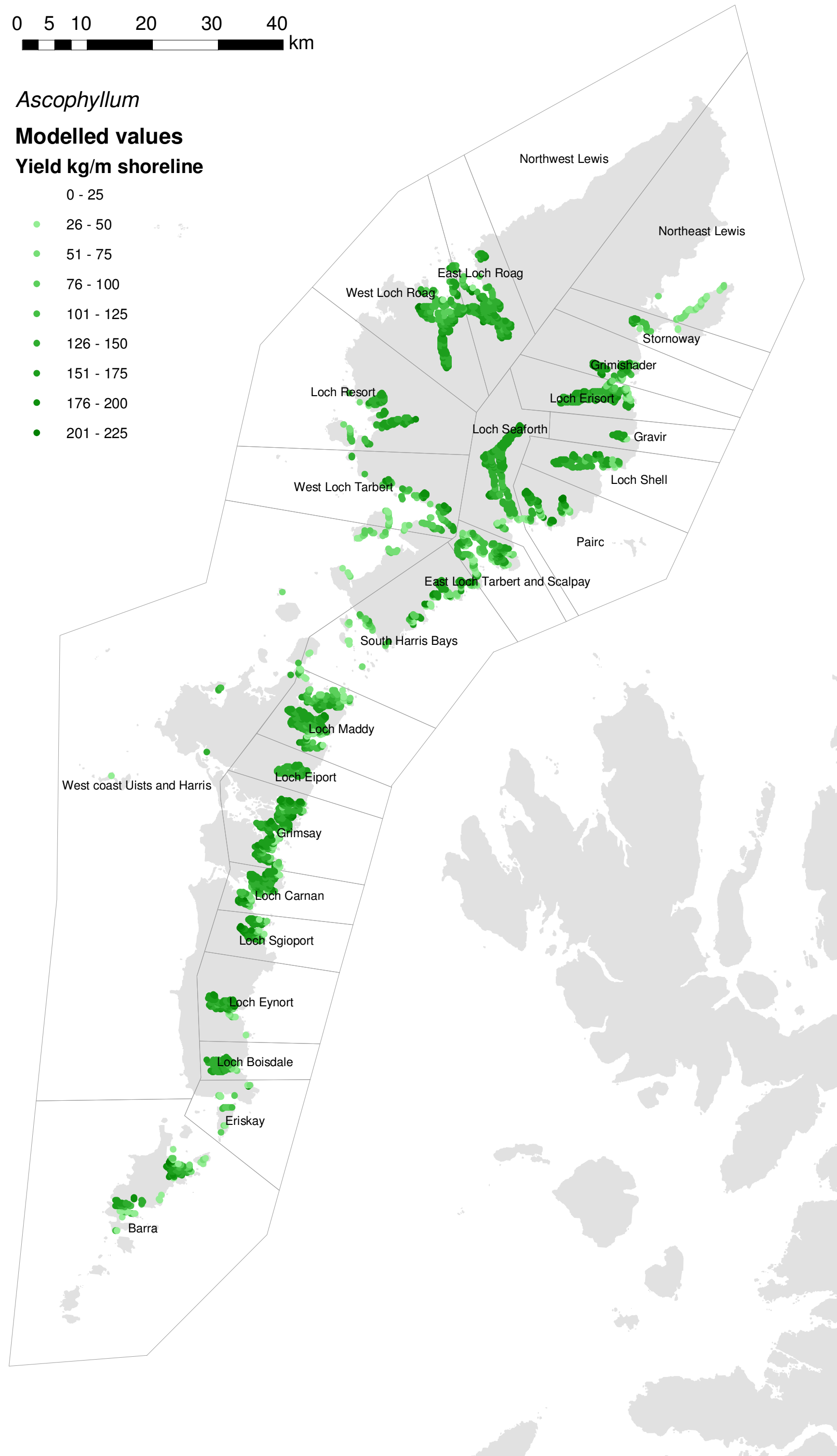


Fig. 12. *Predicted* Ascophyllum *biomass in kg per m of shoreline across the Outer Hebrides Most estimates exceeded 76 kg/m.*

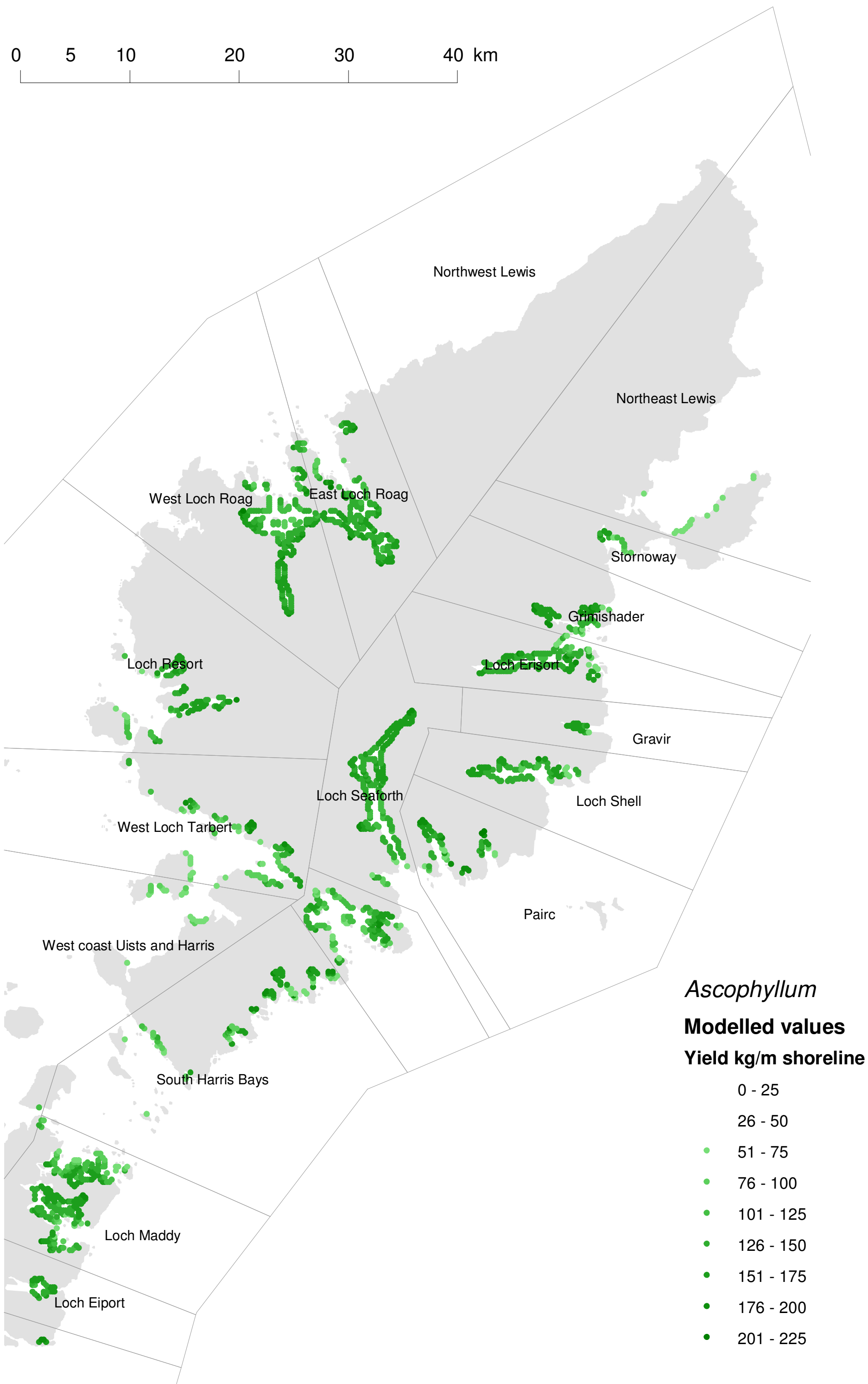


Fig. 13. *Predicted* Ascophyllum *biomass in kg per m of shoreline for Harris and Lewis.*

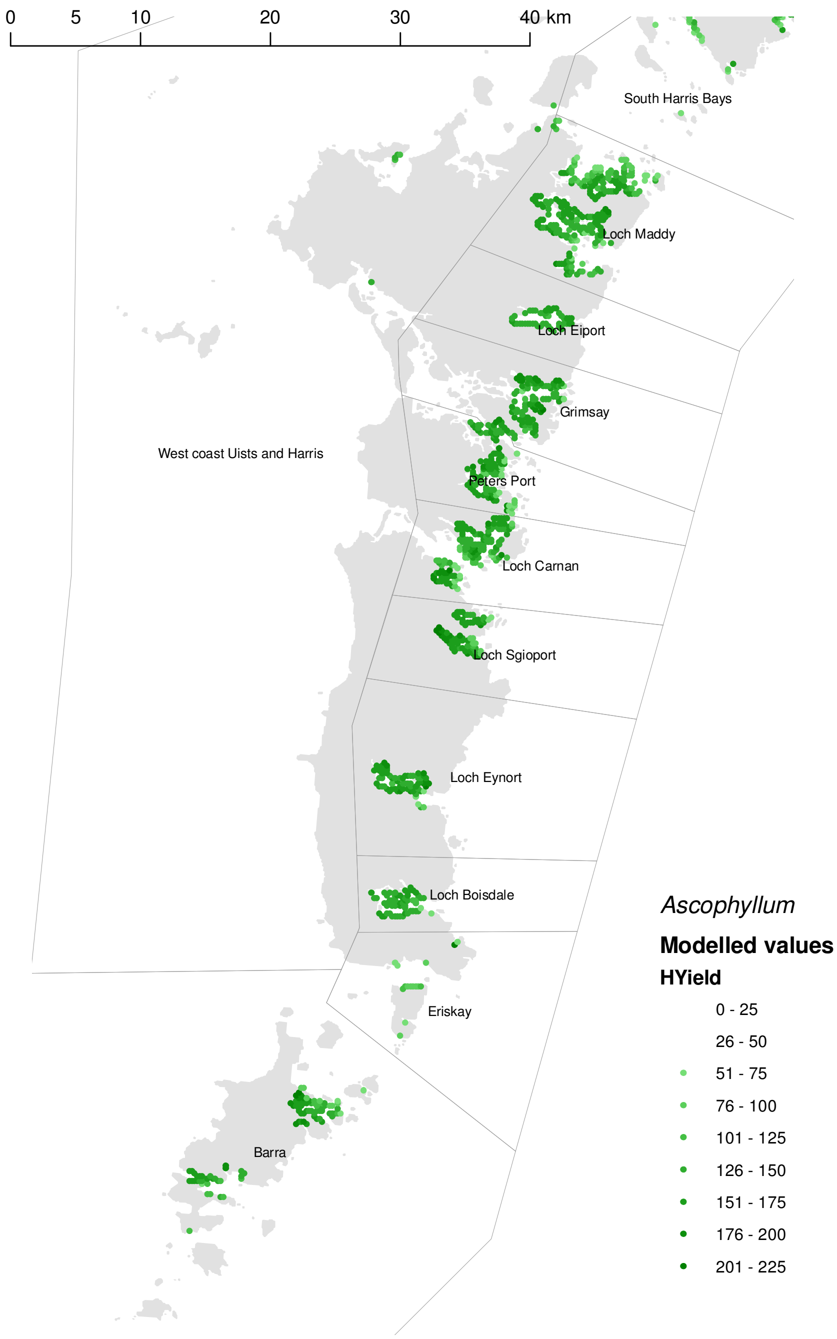


Fig. 14. *Predicted* Ascophyllum *biomass in kg per m of shoreline for Barra, South Uist, Benbecula and North Uist.*

Areas where *Ascophyllum nodosum* is predicted to be abundant are shown in Figs 12, 13 and 14.

4.6.2 *Subregions: Estimates of Ascophyllum biomass across local areas*

A slightly different approach was taken to estimation of the total biomass in subregions from that used for estimating yield in kg per m shoreline at point locations . The total length of coastline in the subregion, L_{reg}, in m was multiplied by the average width, W_{avg}, of the *Ascophyllum* bed in m, the average weight per unit area of *Ascophyllum* in kg/m^2, M_{avg} and the proportion of suitable habitat P_{suit} in the subregion. Wave fetch for each grid node in $\log_{10}$ km was classed into 0.1 intervals. Average values for bed width, weight per unit area and probability of presence were obtained by averaging estimates across the *i* wave fetch classes, weighted by the number of grid nodes, n_i, in each fetch class. Thus, for average width:

$$W_{avg} = \frac{\sum_i W_i n_i}{\sum_i n_i} \quad \text{(equation 8)}$$

for average weight per unit area:

$$M_{avg} = \frac{\sum_i M_i n_i}{\sum_i n_i} \quad \text{(equation 9),}$$

and for probability of presence of *Ascophyllum*.

$$P_{Asco,Subregion} = \frac{\sum_i P_i n_i}{\sum_i n_i} \quad \text{(equation 10)}$$

Finally:

$$W_{Asco,Subregion} = L_{Reg} \ x \ P_{Asco} \ x \ W_{avg} \quad \text{(equation 11)}$$

The method described above gives estimates of the total biomass of *Ascophyllum* per subregion. This approach was also used as the basis for estimating biomass exceeding a specified threshold weight per unit area, and thus amenable to harvesting. This was achieved using a threshold parameter, t_i , coded as zero or one depending on whether the predicted weight per area M_i was above the chosen threshold. Above-threshold biomass estimates per subregion were calculated by substituting $t_i n_i$ for n_i in equations 8 to 10.

Our estimates of the total biomass of *Ascophyllum nodosum* ranged from 154000 tonnes to 185000 tonnes (Table 4), depending on the method and data used to estimate the per-area yield (kg/m^2). The lower estimate was produced if *Ascophyllum* yields were assumed to be the same across all latitudes and without a trend in yield across grades of wave exposure. The higher estimate was produced with a south-to-north increase in yield, largely because most of the suitable wave-sheltered habitat was to be found in the northern half of the Outer Hebrides. The earlier 2004 survey had covered more wave-exposed parts of the coast and showed a greater decline in yield across the wave fetch spectrum, resulting in a lower, intermediate estimate (170000t total). Most of the *Ascophyllum* biomass was on shores with a relatively high yield per km, >60t/km, approximately equivalent to the value of 100 tons per mile considered by Walker (1947a) to be the minimum needed for harvesting.

From the model based on 2004 and 2010 data combined (170000t total), the largest percentage of the total biomass was predicted to be found on Lewis (69000t, 41%), with North Uist the next most abundant (38000t, 22%), followed by South Uist (32000t, 19%) and Harris (27000t, 16%), Barra having very little (2%).

4.6.3 *Harvesting scenarios: Biomass within range of existing and future landing points*

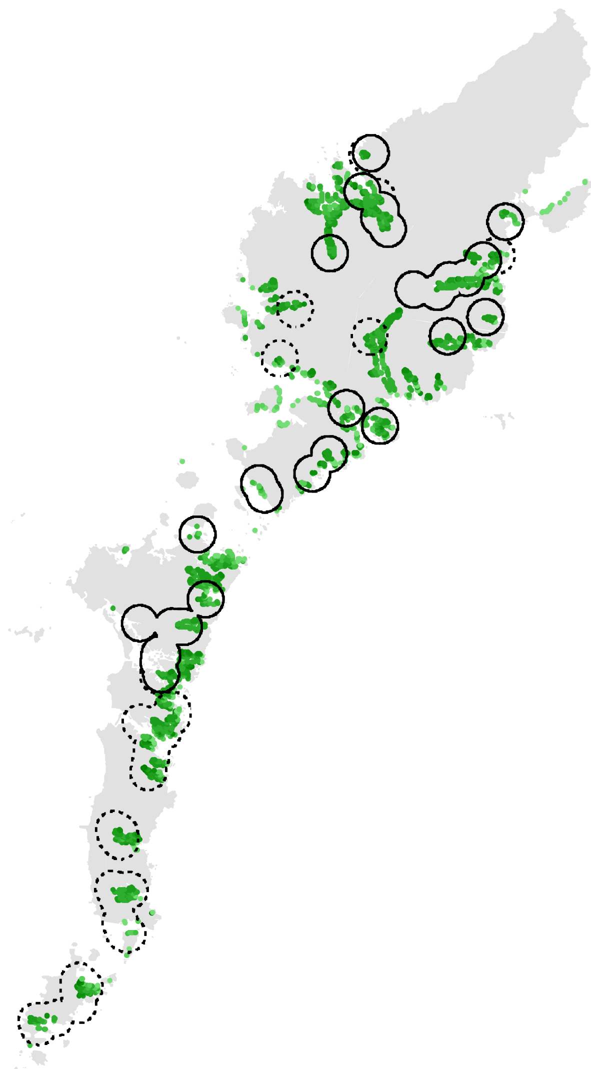


Fig. 15. *Areas <3km from current (solid lines) and potential (dashed) landing points.*

Current practices of hand cutting and mechanical harvesting combined with road transport of harvested weed allow harvest of rockweed only within 3km of landing points with good road access. Cut weed requires towing by small boats to landing points and this is difficult and costly in terms of fuel over greater distances. The harvestable tonnage of *Ascophyllum* is thus restricted to the area within 3km of the currently used set of landing points (Fig. 15). Any expansion of the industry would require a larger set of landing points to allow access to more *Ascophyllum* biomass. Some of these potential landing points would need the development of further infrastructure (roads, turning areas, jetties and slipways) to enable access by large road vehicles and to allow transfer of rockweed to road trailers.

Current and potential future landing points were identified using local knowledge and site visits during the survey period in summer 2010. Although this list cannot be considered as exhaustive, it represents a realistic increase in the degree of access to the resource. Further consideration of areas with suitable road access to the coast may yield more suitable sites. Grid nodes within the 3km radius of currently used and potential future landing sites were identified and scored as such. The approach outlined in 4.6.2 was used on these two subsets of model grid nodes to produce estimates of harvestable *Ascophyllum* in each sub region (Table 4, below).

The present harvesting industry is estimated have access to 61000 tonnes of *Ascophyllum*, only 36% of the total. Most of this is in Lewis (33000t), with the remainder almost equally divided between Harris (12000t) and North Uist (13000t). With a larger range of landing sites, Fig. 15, this could rise to 97000t or 59% of the total available.

Table 4. Estimates of total biomass of *Ascophyllum nodosum* (1000s tonnes) by region in the Outer Hebrides. Values are shown for three alternative methods for calculating mass per unit area for regions at different latitudes and with different lengths of coastline graded by wave exposure. The shaded column shows the biomass within 3km distance of currently used landing points, and the rightmost column gives the biomass <3km from a larger set of potential landing sites.

			Average 2010		2010 data Latitude only		2010 and 2004 data: Fetch and Latitude			
			All	>60 t/km	All	>60 t/km	All	>60 t/km		
Island	Region	Loch							Current	Full
Barra		Barra	6	5	5	4	4	3	0	3
Barra Total			**6**	**5**	**5**	**4**	**4**	**3**	**0**	**3**
Harris	Southeast Harris	East Loch Tarbert and Scalpay	8	7	9	9	9	8	7	7
		South Harris Bays	7	6	9	8	8	7	5	5
	West Harris	Loch Resort	4	4	6	6	6	5	0	2
		West Loch Tarbert	4	4	5	5	5	5	0	1
Harris Total			**23**	**22**	**29**	**28**	**27**	**25**	**12**	**15**
Lewis	East Lewis	Gravir	1	1	2	2	2	2	2	2
		Grimishader	3	3	4	4	4	4	3	4
		Loch Erisort	8	8	11	11	11	11	8	8
		Loch Seaforth	9	9	12	12	11	11	0	4
		Loch Shell	4	4	5	5	5	5	3	3
		Pairc	3	3	4	4	4	3	0	0
	North Lewis	Northeast Lewis	1	1	2	2	1	1	0	0
		Northwest Lewis	0	0	0	0	0	0	0	0
		Stornoway	1	1	2	1	1	1	1	1
	West Lewis	East Loch Roag	11	11	15	15	15	14	14	14
		West Loch Roag	12	12	17	16	16	16	3	3
Lewis Total			**53**	**52**	**73**	**72**	**69**	**68**	**33**	**38**
North Uist	East North Uist	Grimsay	9	8	9	9	9	8	1	1
		Loch Eiport	7	7	8	8	7	7	6	6
		Loch Maddy	21	20	24	24	22	21	6	6
North Uist Total			**37**	**36**	**41**	**40**	**38**	**37**	**13**	**13**
South Uist	East South Uist	Loch Boisdale	4	4	4	4	3	3	0	3
		Loch Carnan	12	11	12	12	11	11	0	11
		Loch Eynort	4	4	4	4	4	3	0	3
		Loch Sgioport	5	5	5	5	5	5	0	5
		Peters Port	9	9	9	9	8	8	2	7
		Eriskay	1	1	1	1	1	0	0	0
South Uist Total			**35**	**34**	**35**	**34**	**32**	**30**	**2**	**29**
West	West coast Uists and Harris		2	1	2	2	1	1	0	0
West Total			**2**	**1**	**2**	**2**	**1**	**1**	**0**	**0**
Grand Total			**154**	**150**	**185**	**180**	**170**	**165**	**61**	**97**

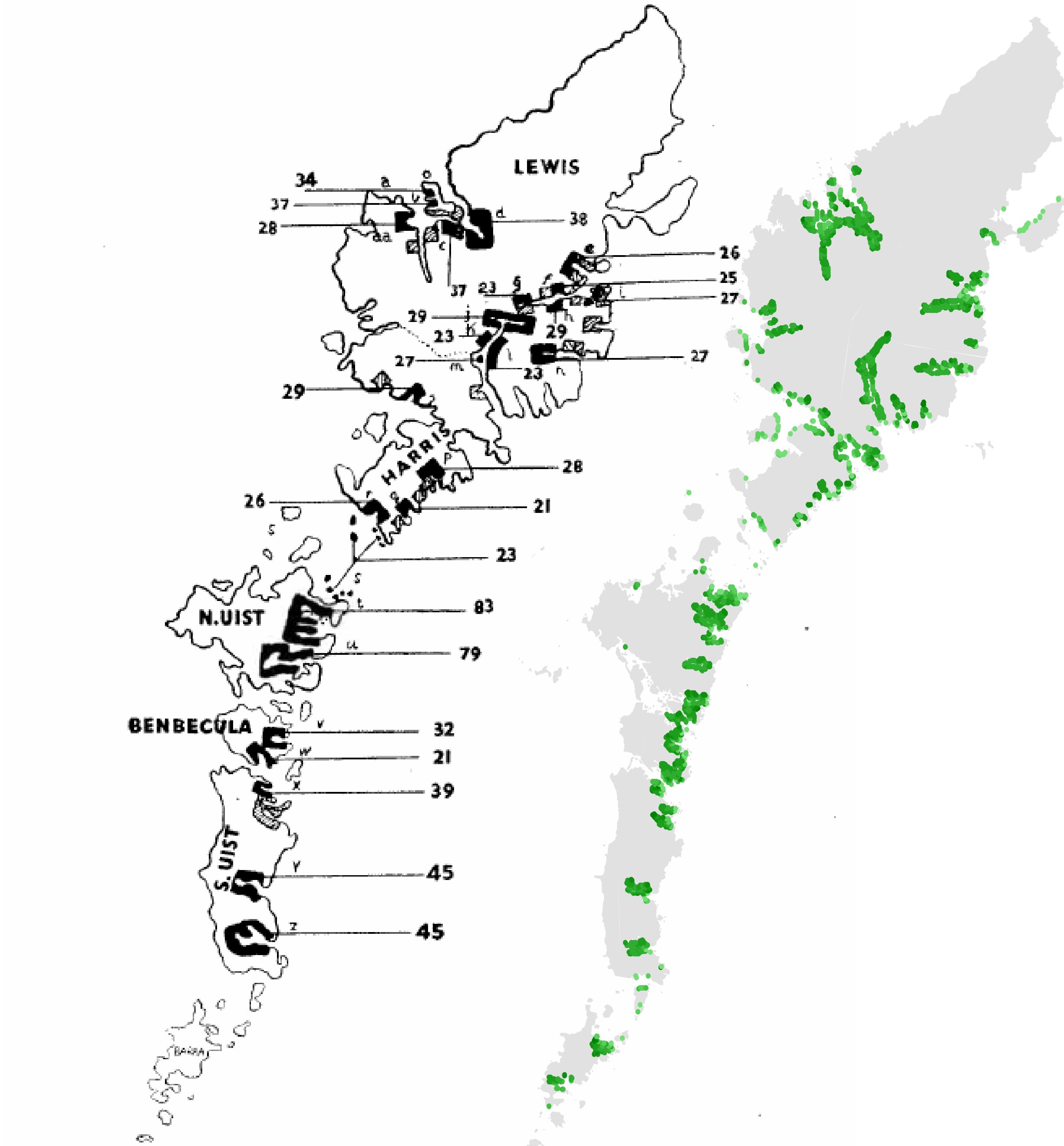
With a recommendation that areas should be left for four years between harvesting for plants to regrow (Sharp 1987), the annual harvest for the currently exploited resources should be no more than 25% of the biomass within the 3km range from landing sites (Table 4). This gives an upper limit for the annual harvest for the current set of landing sites of 15000t, and 24000t if a larger set of landing sites were developed. With the need to leave some of the plant behind during harvest to let this regrowth occur, the advisable upper limit on the annual harvest should be less than 25% of the total biomass.

4.6.4 *Comparisons with Scottish Seaweed Research Association estimates from 1945-1946*

The rockweed resources of the Outer Hebrides were the subject of an intensive set of surveys and mapping exercises from 1945 to 1946, with the same aim as this study. A summary of the results of these surveys was published in 1947 (Walker 1947a), with three detailed and one summary unpublished reports held in the archives of the Institute for Seaweed Research (SSRA Reports 15, 74, 75 and 88) These archives were transferred to the Scottish Marine Biological Association at the Dunstaffnage Marine Laboratory in Oban, and are still held in the same library of the now-renamed Scottish Association for Marine Science at the Scottish Marine Institute.

The *Ascophyllum nodosum* resource in the 1940s was estimated as 123000 tonnes (converted from imperial tonnes). The geographical extent of the resource determined in the 1940s was broadly similar to that of 2010 (Fig. 16). Some differences can be seen. Loch Resort in Harris was not considered as a significant area for *Ascophyllum* in the 1940s, nor was the area to the south east of South Uist around Grimsay. Barra was not included in the 1945-46 survey.

While the overall biomass estimated in the two surveys was broadly similar, there were notable differences in the estimates for each area (Table 5). *Ascophyllum* biomass in Loch Maddy, for example, was estimated as 39000 tonnes by Walker but only 21000t in this study, making the SSRA estimated total for North Uist much larger than in this study. Interestingly, this was nearly half the original value, itself doubled by Walker to account for the boulder habitat in the area. Our estimate for Lewis (68000t) was over seven times Walker's estimate (9400t), with more seaweed suggested for every subregion. Most of this difference was due to the omission of areas from the SSRA survey, such as Loch Roag Beag (a southern extension of West Loch Roag), Loch Resort, the southern end of Loch Seaforth, and the Pairc area (see Fig. 16). As a consequence of the complete consideration of all areas of the coastline in this 2010 study, Harris and Lewis combined were estimated as having 93000t in 2010, but were represented as only having 29000t in 1947. South Uist and Benbecula, on the other hand, emerged as similar in 1947 and in 2010, reflecting the similarity of the areas identified for *Ascophyllum*.



MAP 4.—OUTER HEBRIDES. Showing general surveys [hatched] 50–100 tons/mile and detailed surveys [black] over 100 tons/mile. The figures shown give the weed density in tons/acre.

Fig. 16. *The distribution of* Ascophyllum nodosum *biomass in the 1940s in areas with >100 tons per mile as estimated by Walker (1947, left) shown alongside estimates from this study (right).*

Table 5. Comparison of estimated *Ascophyllum* biomass by area between this study and the Scottish Seaweed Research Association estimates (Walker 1947b). Current estimates are shown for the model based on 2010 and 2004 data, including wave fetch and latitude trends.

			Now			SSRA		
Island	Region	Loch	tonnes	km	ha	tonnes	km	ha
Barra	West Coast South	Barra	3143	33	33			
Barra Total			**3143**	**33**	**33**			
Harris	Southeast Harris	East Loch Tarbert and Scalpay	8430	55	63			
		South Harris Bays	6839	47	57	1067	8	41
	West Coast North	Loch Resort	5404	32	33			
		West Loch Tarbert	4689	30	35	[1]18474	24	1339
Harris Total			**25362**	**165**	**188**	**19540**	**32**	**1380**
Lewis	East Lewis	Gravir	1683	10	10			
		Grimishader	4090	23	25	674	3	25
		Loch Erisort	10674	63	66	1628	10	63
		Loch Seaforth	10900	67	68	2063	18	77
		Loch Shell	4548	28	28	203	2	7
		Pairc	3473	22	24			
	North Lewis	Northeast Lewis	1369	8	13			
		Northwest Lewis	0	0	0			
		Stornoway	1262	7	8			
	West Coast North	East Loch Roag	14374	80	80	[2]4873	27	132
		West Loch Roag	15556	87	88			
Lewis Total			**67929**	**394**	**411**	**9441**	**27**	**132**
North Uist	East North Uist	Grimsay	8328	62	62			
		Loch Eiport	6946	51	52	19438	22	246
		Loch Maddy	21289	152	160	39211	30	472
North Uist Total			**36563**	**266**	**274**	**58649**	**51**	**718**
South Uist	East South Uist	Loch Boisdale	3289	30	30	11614	20	257
		Loch Carnan	10554	84	87	2461	10	63
		Loch Eynort	3382	29	29	7480	14	165
		Loch Sgioport	4567	37	37			
		Peters Port	8161	63	66	[3]13976	33	556
	West Coast South	Eriskay	446	5	5			
South Uist Total			**30400**	**249**	**254**	**35530**	**77**	**1041**
West	West Coast South	West coast Uists and Harris	1329	10	14			
West Total			1329	10	14			
Grand Total			**164725**	**1116**	**1173**	**123160**	**187**	**3272**

Notes:

1. Islands and Skerries of the Sound of Harris; 2. East and West Loch Roag combined; 3. Benbecula total

4.7 Application of the assessment methodology on a national scale

The process developed here can be directly used for delivering assessments of species-specific biomass estimates on a national scale, without substantial modification:

(1) Survey estimates of biomass per unit area and habitat extent as a function of local influences, here predominantly wave exposure, are needed to build models that predict location-specific biomass estimates from map data. The quantity of survey data used to produce these models will partly determine the confidence of the estimates produced. Subtidal habitats are more difficult to sample than intertidal habitats and this difficulty and the additional costs involved should be considered when designing further survey work. Existing records for the presence of kelps (*Laminaria* species), for example, could be used to make preliminary models for an initial biomass estimate, although it must be recognised that algal biomass can change markedly over time (e.g. Walker 1956).

(2) Map data are needed for coastline length and habitat extent, including bottom type (rock or sediment). The wave fetch model used here needs only coastline data, and has already been used to produce a 200m-scale map of wave exposure for the area within 5km of the whole of the UK coastline.

(3) For subtidal algae such as the kelps, more detailed bathymetry of the nearshore coastal seas (<50m depth) would be needed to define the areas of habitat available. Water clarity is an important factor in determining the depth distribution of subtidal algae and this should be taken into consideration. Remotely sensed satellite estimates of ocean colour are a good proxy for clarity (light attenuation) and should be included in models predicting biomass from the extent and depth of available habitat.

(4) Estimates of kelp biomass produced for Scotland in this way could be directly compared with the estimates produced by the Institute for Seaweed Research in the early 1950s (Walker 1953).

5 Digital resources

(1) Estimates of the yield of *Ascophyllum nodosum* per m of shore line at 200m intervals are provided in a text file (ModelYieldAscophyllumOuterHebrides.csv), with the Ordnance Survey grid reference coordinates for each node.

(2) An ESRI ArcGIS shapefile with the subregional boundaries used in this study (OuterHebridesSubRegions.shp).

(3) Raw data collected during the survey per 0.25m^2 quadrat and per site, including information on *Ascophyllum* vertical limits, shore profiles, tidal conditions and observations made at the time of surveys (RawData1.xls to RawData4.xls).

(4) Calculations of average yields and plant lengths by site (SiteYields.xls)

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7 Appendices

7.1 Text of the Consultation Letter sent in June 2010

Re: **Mapping the Seaweed Resources of the Outer Hebrides**

A Scottish Enterprise & Highlands and Islands Enterprise funded project

Dear (*Stakeholder name inserted here*)

We are beginning a project to assess the harvestable seaweed resources of the Outer Hebrides in partnership with the Hebridean Seaweed Company. An essential step in the development of a harvesting industry for natural seaweeds is the assessment of the quantity of seaweed that can be sustainably collected each year. The size of the harvest should neither compromise future yields nor the role of seaweeds in supporting the natural environment – the marine ecosystem. Our project focuses on the only species of seaweed currently harvested in the area, the egg wrack (Latin name *Ascophyllum nodosum*).

The project involves two months of surveying along the sheltered coasts of the Outer Hebrides, mostly in sea lochs and bays along the eastern coasts of the Uists, Harris and Lewis. Two or three sites within each loch will be visited each day around low tide. At each site we intend to completely remove plants from 12 50x50cm areas ($3m^2$ per site) to measure the size of plants and the weight per unit area. We will also measure the vertical and horizontal extent of the seaweed beds using surveying equipment. This data will be combined with map information on coastline length, intertidal area and wave exposure to produce the best possible estimate of seaweed biomass in the area. As this is a short study we will not be able to directly measure regeneration of weed after harvesting, but we will use previously reported estimates of regeneration rates to produce possible sustainable harvesting scenarios.

An essential component of the project is to engage with key stakeholders such as yourselves in order that your expertise can be considered in our methodology and when guiding regulation going forward. As such, we would like to collect your ideas and thoughts on our assessment of the seaweed resources. The type of information we seek to gather includes questions around:

- Do you have comments on our proposed methodology?
- What would you like to see from the project to inform better management of the seaweed resource?

The biomass and harvesting estimates will replace those last made in the 1940s and should allow a comparison with the amount of resource then thought to be available for harvest. We can provide a fuller account of our methods prior to any discussions with you, if it would be of interest

- What are your primary concerns in relation to the methodology proposed and the potential seaweed resource available for harvest?
- Are there issues regarding ownership and/or competing use of the intertidal zone?

We hope that, following this letter, you would be open to further engagement around our method and how the results may influence the harvesting industry. We anticipate contacting you by again in the coming weeks to discuss these questions in more depth and, in the meantime, please feel free to contact us directly.

Yours sincerely,

Dr Michael T. Burrows
e: mtb@sams.ac.uk t: 01631 559237

Mr Martin Macleod, Hebridean Seaweed Company
e: martin@hebrideanseaweed.co.uk t: 01851 70125

7.2 *Example of Site Survey recording sheet*

Date/Time: 11 - 09 - 10 **Site / Loch:** EAST LOCH TARBERT (SCALPAY)

Time of LW: 15.30 **Port for tide predictions:**

Comments: NEAR HARBOUR, SEMI-EXPOSED EAST LOCH TARBERT

GPS Waypoint Top: 57°52.442N 006°41.948W **Bottom:** ROCKY WITH SILT/SHINGLE

Grid Ref:

GOOD FOR HARVESTER, NOT BIG ROCKS RELATIVELY SMOOTH SHORE

Time: 15.00 **Tide Height:** 0.8 **Pressure:** 1005 **Tide adjust for pressure:** 0.75

Ht of theodolite above water: 4.72 + 0.75 = 5.47

MHWS height: 5.0 m **Theodolite reading @ MHWS:** 0.47

Length of transect line: 18m **Divs:** 1.8

Shore Profile:

Along Line	1.8	3.6	5.4	7.2	9	10.8	12.6	14.4	16.2	18
Pole reading	4.58	4.21	3.93	3.21	2.7	2.15	1.7	1.21	0.91	0.47

***Ascophyllum* vertical limits**						Average	Line position
Lower	4.12	4.21	4.03	4.09	4.24	4.13	4.0
Upper	1.72	1.9	1.95	1.71	1.75	1.80	11.7

Range: 2.33 ÷ 2 = 1.165

	Low (mid + 0.5m)	Mid (lower limit - range/2)	High (mid – 0.5m)
Teodolite reading	3.46	2.96	2.46
Line position	6.5	8.9	9.9

Quadrat measures: GOOD WEED (LONG)(DARK BROWN) MOSTLY ON ROCKS, SILTY

	Low		**Mid**		**High**	
	Lengths x 4 (cm)	Wt	Lengths x 4 (cm)	Wt	Lengths x 4 (cm)	Wt
1	—	—	150, 170, 202, 200	6.5	—	—
2	110, 170, 192, 93	4.1	—	—	121, 173, 90, 157	6.2
3	170, 220, 175, 210	5.4	90, 89, 100, 102	8	139, 157, 160, 73	3.2
4	89. 85, 92, 150	3.9	—	—	55, 90, 101, 25	2.3