Marine Research Sub-Programme
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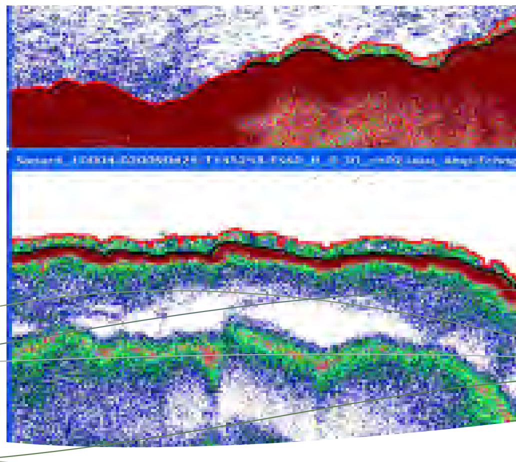
SeaChange
Casadh na Taoide

Development of a Methodology for the Quantitative Assessment of Ireland's Inshore Kelp Resource

Project-Based Award, Final Summary Report



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Marine Research Sub-Programme 2007-2013

Project Based Award

Development of a Methodology for the Quantitative Assessment of Ireland's Inshore Kelp Resource

(Project Reference: PBA/SW/07/002 (01))

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Project Partners:	University College Cork and Envision Mapping Ltd.
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Executive Summary

Kelp dominate the shallow subtidal in temperate parts of the world and are the largest and most complex of the brown algae. In Europe they are of major economic importance for the hydrocolloid industry as a source of alginates. France and Norway exploit this resource, with France harvesting 60,000 tonnes of *Laminaria digitata* annually and Norway harvesting 160,000 tonnes of *Laminaria hyperborea* annually. Extracts from kelp are used by the cosmetic and agrochemical industries and for biotechnological applications. In a report published in November 2000, the National Seaweed Forum identified the potential for developing a mechanical kelp harvesting industry in Ireland. Specific emphasis was placed on the likely ecological impacts of this activity. The Forum identified the requirement for further basic knowledge and information before sustainable harvesting practices could be explored. One core item of information required was the amount of kelp resource in Ireland. However, no reliable methodology exists for accurate quantification of kelp biomass on a spatial scale appropriate to harvesting of the resource.

Intermediate spatial scales (100m to 10's km) are likely to be the most relevant to marine resource assessment in relation to the development of mechanical harvesting of macroalgae. Satellite imagery and aerial photography are unable to provide data of sufficient resolution on kelp biomass for harvesting purposes. However, a number of preliminary investigations have indicated that acoustic techniques may have the potential to provide the required spatial coverage of a harvestable area at a sufficient resolution. Few of the preliminary studies have rigorously compared the efficiency of the estimation of macrophyte density and biomass using acoustic techniques with direct measurement from observations. Here we use a commercially available Single Beam Echosounder (SBES) with modified signal-processing software to determine the spatial distribution of kelp in both wave-exposed and sheltered sites at two locations on the south and west coasts of Ireland and to relate derived acoustic parameters to verified estimates of kelp density and biomass provided from SCUBA diver ground truthing. Three surveys were conducted in the south of Ireland so that seasonal changes could be examined and one survey was conducted (spring) on the west coast.

The biological surveys showed a consistent mean kelp biomass across the sites irrespective of the level of exposure. Kelp biomass varied seasonally with lower biomass following winter storms and before the main growth period. Examination of the morphological characteristics of *L.. hyperborea*, showed a consistent relationship for all surveys between the stipe length of individual specimens and their total biomass (stipe and lamina mass).

During the acoustic surveys it was apparent that the record from the echogram of the 200kHz channel showed substantially less backscatter in the water column than that of the lower frequency (38kHz) channel. This resulted in a clearer definition of the seafloor and kelp canopy from the higher frequency record and has important implications for the autodetection of the kelp as this would likely lead to a significant reduction in the amount of operator input needed to process the data. The project demonstrated the value of smoothing and aggregation of the data in the generation of kelp resource maps by reducing variability in the signal associated with outliers; thus allowing production of estimates of kelp cover at a scale which is pertinent to harvesting practices and resource assessment.

The acoustically determined depth profile of the kelp beds showed a highly significant relationship with the detailed plant data obtained from diver sampling and observations. A strong relationship was also recorded between diver derived kelp biomass and the acoustically measured Percentage Volume Inhabited (PVI) and bio height (height of the kelp above the substrate).The smoothing technique applied to the data minimises the effects of the error associated with outliers. The relationship between acoustic parameters and sampled biomass, obtained after smoothing, appears consistent and can be used to predict kelp biomass to within the limits of error required by the terms of the project. The regression equation relating kelp biomass to the acoustic output obtained from data for the south-west surveys and applied to the acoustic data for the west coast survey, correctly predicted the higher biomass found on the west coast. This result is very reassuring and indicates that the acoustic survey approach may be used in situations outside of the conditions of the surveys carried out in this investigation.

The acoustic surveys demonstrated a clear transition from dense kelp beds to sparse or barren areas at both survey sites. This has important implications for the detection of dense stands of kelp and the estimation of biomass from the viewpoint of potential harvesting - dense kelp would appear to be well defined spatially and the transition zone can be confidently mapped. However, the acoustic technique could not be used to distinguish between the two principal species of kelp, *L. hyperborea* and *L..digitata*.

The main aim of the project was to develop and demonstrate an acoustic methodology for the estimation of kelp biomass based on a low-cost commercial marine acoustic system and modification of the standard software. It is considered that the primary aim of the project has been achieved. The approach will be of significant value to regulatory authorities for the monitoring of healthy kelp beds and their associated fauna and flora. It will also provide a scientific basis for future kelp harvesting trials, be instrumental in developing appropriate management plans for such practices and will aid in the evaluation of the recovery in harvested areas.

1. Introduction

1.1. Background

In October 1999, the newly formed National Seaweed Forum set out to evaluate aspects of seaweed research and the status of the associated industry in Ireland. In its November 2000 report (National Seaweed Forum, 2000), the Forum identified the potential for developing a mechanical kelp (*Laminaria digitata* and *Laminaria hyperborea*) harvesting industry in Ireland. Specific emphasis was placed on the likely impacts of this activity. The Forum identified the requirement for further knowledge and information before sustainable harvesting practices could be explored including:

- current harvesting practices and management strategies in other countries, especially France and Norway;
- environmental impacts of mechanical harvesting methods; and
- the amount of resource in Ireland.

A number of reviews have contributed towards the understanding of these topics (Werner and Kraan, 2004; Kelly, 2005; Hennequart et al., 2006), with some reports including estimates of kelp biomass around the Irish coast derived from desk studies (Hession et al., 1998; Werner and Kraan, 2004). However, there is no reliable methodology to accurately quantify kelp biomass and therefore, a full and accurate assessment of the kelp resource available for harvesting has not yet been achieved.

Sea Change (2007-2013) set targets for the seaweed sector to develop a sustainable and scientifically based harvesting of kelp and regular use of seaweed in biotechnology. The seaweed production and processing sector is predicted to play an increasing role in marine resource utilisation, in the context of marine spatial planning in the coastal zone.

In Europe, kelp are of major economic importance for the hydrocolloid industry as a source of alginates. France and Norway exploit this resource, with France harvesting 60,000 tonnes of L. *digitata* annually and Norway harvesting 160,000 tonnes of *L.. hyperborea* annually (Werner and Krann, 2004). Extracts from kelp are used by the cosmetic and agrochemical industries and for biotechnological applications. Examples of how the products derived from the alginates are used include; as a stabilizer/emulsifier in the textile industry; as an additive to ice cream or dairy product; and in the development of insoluble fibres for bandages and wound dressings (www.seaweed.ie). Worldwide sales of alginates in 2009 were in the region of 26,500 tonnes, with a market value of approximately US$318 million (Bixler and Porse, 2010). The industry has seen a rise in seaweed costs, reflecting shortages as a result of limited seaweed supplies.

1.2. Scales of Analysis

The method of assessing the available kelp resource around the Irish coastline depends on the spatial scale of the area planned for exploitation. Any approach will need to be appropriate to the scale of analysis, cost effective and provide sufficient resolution so that quantitative estimates of the kelp resource can be calculated. At the smallest scale, i.e. tens of metres, SCUBA diving surveys are likely to be the best method of providing accurate estimates of kelp biomass. The use of SCUBA, while it can provide high resolution data on kelp distribution and biomass, by both destructive and non-destructive techniques, is very restricted in its spatial coverage and is also very expensive in terms of labour costs. At the largest scale, i.e. greater than tens of kilometres (10's km), there may be the requirement to estimate the total standing stock of kelp beds around the entire coast of Ireland. Optimal methods for surveys at this scale would involve the use of aerial photography or high resolution satellite imagery accompanied by appropriate ground truthing. Some studies that have used aerial photography to determine the large-scale distribution of macroalgae include North et al. (1993), Stekoll et al. (2006) and Anderson et al. (2007). Satellite imagery has been employed by Deysher (1993), Guillaumont et al. (1993), Simms and Dubois (2001), Gullström et al. (2006), Stekoll et al. (2006) and Anderson et al. (2007). Each of the techniques examined was limited by the state of the tide, currents, weather conditions and depth penetration of the optical sensors used. Satellite imagery is a suitable tool for shallow water environments, down to a depth of approximately 7m (Simms and Dubois, 2001; Gullström et al., 2006). However, this covers only a portion of the zone actually occupied by kelp. High resolution aerial photography also has the capability to determine the spatial extent of subtidal kelp beds but is reliant on good weather conditions and is also depth limited. The accuracy of aerial photography was shown to improve if the bathymetry of the seabed was included in the analysis (Gagnon et al., 2008), however this makes the technique more complicated and time consuming.

The intermediate spatial scale (100m to 10's km) is likely to be the most relevant to marine resource assessment and the development of mechanical harvesting of macroalgae. In order to optimise spatial coverage of an area and to ensure sufficient resolution, given the limitations of the above techniques, some authors have suggested the use of acoustic techniques (Davidson, 2006; Anderson et al., 2007). Acoustic techniques have been shown to be capable of detecting macrophytes on the seafloor and are capable of reaching the deeper macrophyte beds (McCarthy and Sabol, 2000; Riegl et al., 2005).

1.3. Acoustic and Remote Sensing Approaches

Remote sensing offers the possibility of rapid survey of kelp beds for mapping distribution and estimating density, canopy height and biomass. Satellite or airborne sensors cover large areas, but are limited by the depth of penetration of visible and infrared wavelengths. Even where conditions are suitable for detecting kelp underwater, radiation reflected from the canopy is unlikely to provide information on kelp density or biomass and acoustic techniques may be more applicable. The way in which acoustic energy from transducers interacts with the medium through which it is transmitted and reflected is very complex and has been intensively studied (see introductory texts such as Blondel and Murton, 1997; Lurton, 2002). The analysis of the echo contains much information about the water column and seabed. The major part of the energy reflected is from the seafloor and the peak of this signal is used to pick out the seafloor and determine its depth. However, the 'tail' of the echo has been used to measure properties such as sediment roughness and hardness (Orlowski, 1984). The weaker reflectance from fish in the water column or growth of fauna and flora from the seabed can be detected by echosounders before the bottom is detected and this has been used in fisheries sounders for the detection of both pelagic and bottom-living fish. It has also been used to assess macrophyte distribution and abundance.

A Single Beam Echosounder (SBES) emits a pulse of sound of a fixed frequency and duration that is directed vertically towards the seafloor. The sound reflects from the seafloor back to the transducer, which then converts the sound energy back to an electrical signal and this signal is analysed as a time-trace of the energy. The transducer does not emit another pulse until the echo from the previous pulse has been received and processed. SBES' are the simplest of the SONAR systems and analysis of the echo is much less complex than for swath systems such as sidescan and multibeam systems, which have the additional complication of accounting for the varying 'grazing angles' of sound that travels to either side of the vessel.

Analysis of the soundecho has taken many forms. Some studies have simply used print-outs of the echogram with the seafloor and kelp canopy being discerned by eye (Fortin et al., 1993). This approach combined the traces with geographic positioning to map out macrophytes in lakes. However, automated analysis offers clear advantages and has become more feasible in recent years. Some systems integrate signal strength and time from particular sections of the echo to obtain information on the seabed. This is the basis of the commercial RoxAnn acoustic ground discrimination system (AGDS) (Chivers et al., 1990). Although RoxAnn is designed to discriminate between habitat types, it has also been used for kelp habitat mapping (Hass and Bartsch, 2008). More intensive processes have been developed as research tools, involving the analysis of the total wave envelope (the full shape of the time trace of the echo) to extract a large number of features that characterise the signal. These features are then reduced through principal components analysis (PCA). The survey area is then segmented by analysing the distribution of the components (Preston et al., 2006; Kruss et al., 2006; Kruss et al., 2008).

Fisheries SBES are designed to detect echoes above the seafloor and, although primarily used for the detection of fish, there has recently been much progress in utilising them for the detection of benthic plant cover (Sabol et al., 1996; Schneider et al., 2001; Sabol and Johnston 2001; Sabol et al., 2002; Hoffman et al., 2002; Preston et al., 2006). These studies were all successful in locating the acoustic signals from submerged vegetation. Such hydroacoustic systems can operate at a variety of frequencies and the general consensus is that higher frequency echosounders are likely to be more effective for mapping vegetation (Komatsu et al., 2003; Winfield et al., 2007).

Few studies have rigorously compared the estimation of macrophyte density and biomass using acoustic techniques with direct measurement or observations. Jackson (2003) mapped seagrass beds around Jersey using a Biosonics echosounder and the correlation between results from the echosounder and from diver ground truth stations was found to be strong. Further, Collins (2009) briefly reported on a comparison between echosounder and video; with agreement between the systems increasing with increasing density of macrophytes - in this case, seagrass.

Swath systems have the benefit of much greater spatial coverage. However, the analysis of the signal from swath systems is not as straightforward as that from single beam systems. Methods for the analysis of the signal from sidescan and multibeam systems for ground discrimination (Collins et al., 2002; Cutter et al., 2002) and fisheries (Gerlotto et al., 1999) are being developed. It is probably too early in the development of such approaches for automated analysis of backscatter to be considered as routine.

Lastly in our justification for using SBES, some studies have combined the ability of SBES to discriminate macrobiota with the coverage of swath systems. Noel et al. (2008) have used this approach, combining the information from different remote sources within a Geographical Information System (GIS), to map the distribution of *Laminaria* off the coast of Brittany.

1.4. Kelp: Ecology and Growth

There are five species of kelp indigenous to Ireland; *Alaria esculenta* (L.) Greville; *Saccorhiza polyschides* (Lightfoot) Batters; *Laminaria saccharina* J.V. Lamouroux; *Laminaria digitata* (Hudson) J.V. Lamouroux (Figure 1.1) and *Laminaria hyperborea* (Gunnerus) Foslie (Figure 1.2). Of these, it is only *L.. digitata* and *L.. hyperborea* that form extensive monospecific stands, which are of interest for commercial harvesting. *L.. digitata* has a smooth flexible stipe, oval in cross section. It also has a digitate lamina (see Figure 1.3) and can grow to approximately 2 metres (m) in length. *L.. hyperborea* has a rough and more rigid upright stipe, round in cross section. It too has a digitate lamina and can grow to 2-3m in length.

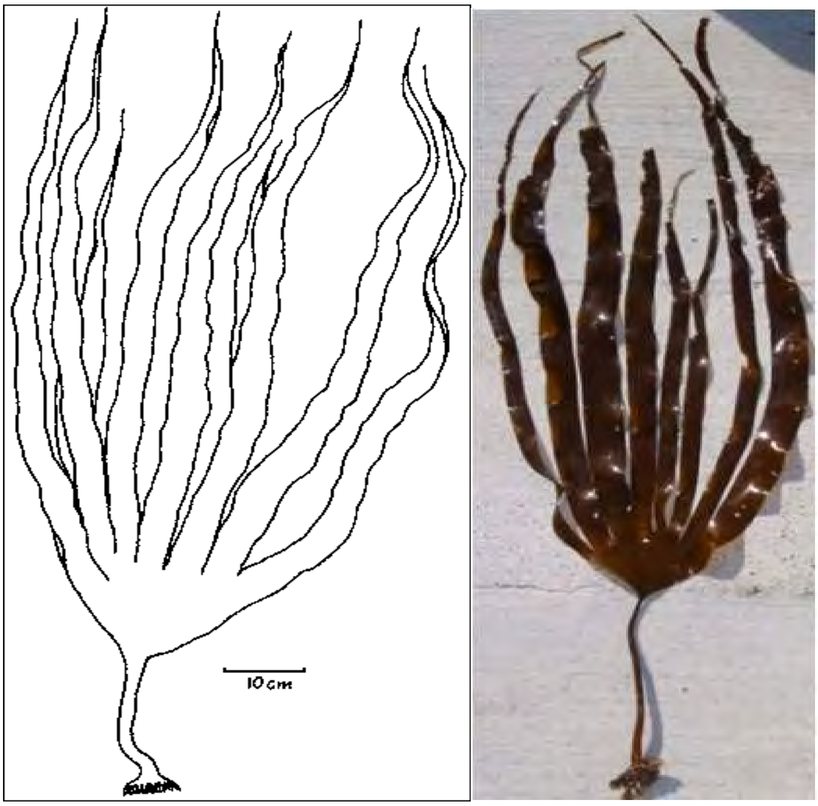

Figure 1.1: Diagrammatic representation and photograph of *Laminaria digitata*.

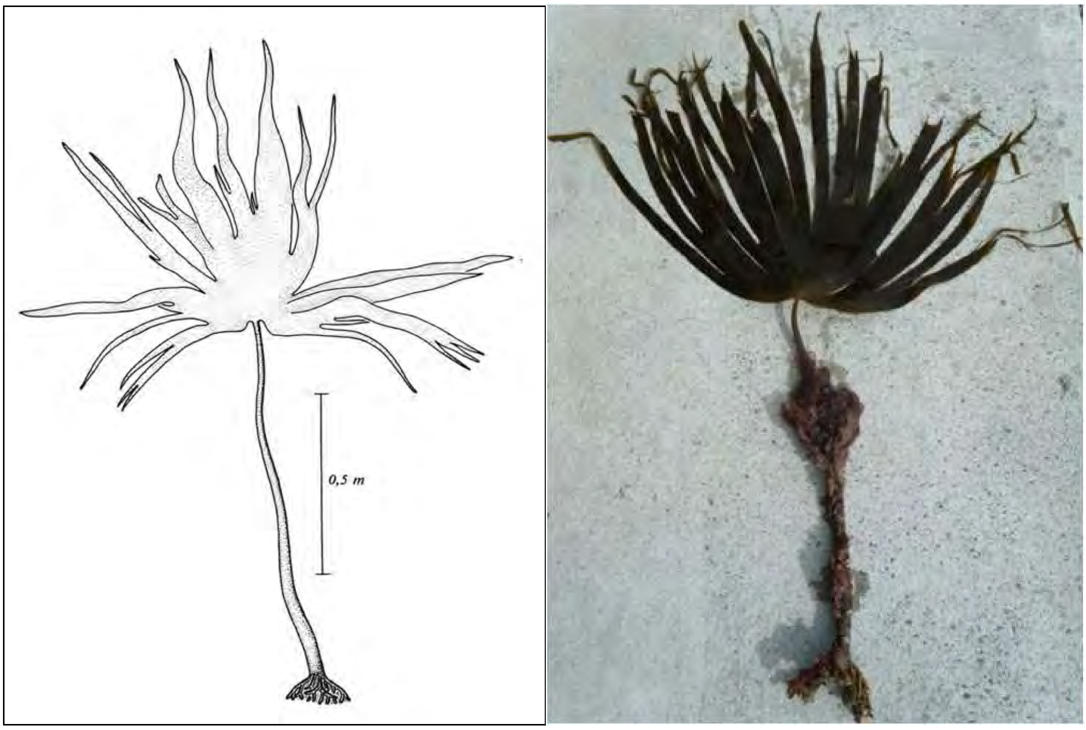

Figure 1.2: Diagrammatic representation and photograph of *Laminaria hyperborean.*

Kelp can be found from the lower intertidal zone, where it is only immersed at extreme low water, and downwards into the subtidal zone. In hard substrate subtidal environments, light levels usually determine the lower limit of algal distribution (Lüning, 1990). This limit is therefore restricted to the shallow subtidal in turbid waters but extends to greater depths in clearer, open coastal waters. *L.. hyperborea* forms dense stands down to depths that receive approximately 5% of the surface irradiance and are absent from depths which receive less than 1% of the surface irradiance. Kelp dominate the subtidal from about 2m below the lowest tide, with *L.. digitata* dominating the shallow subtidal rising into the lower intertidal (Lüning, 1990). The lower limit of *L.. digitata* is restricted by competition for light with *L.. hyperborea* which can overshadow development of juvenile *L.. digitata* plants due to its more rigid upright stipe.

Kelp exhibit a heteromorphic life cycle with an alternation of generations between a microscopic sexual (haploid) gametophyte and a macroscopic asexual (diploid) sporophyte. It is the sporophyte that forms the distinctive dense stands of algae in the shallow subtidal of many temperate rocky shores. The holdfast and stipe of the sporophyte (Figure 1.3) are perennial, with *L.. digitata* specimens living for around 3-5 years and *L.. hyperborea* living for around 10-15 years. The lamina tissue, however, is replaced annually through seasonal growth, with loss associated with the continuous wear of the apical end due to wave action and tidal flows. The meristem, which is located between the stipe and the lamina, is the main site of growth for both *L.. digitata* and *L.. hyperborea*. Growth of this tissue results in an elongation and thickening of the stipe and elongation of the lamina. Growth of *L.. digitata* and *L.. hyperborea* is seasonal and is controlled by an endogenous circ-annual clock (Schaffelke and Lüning, 1994). The highest growth rates occur from late winter to late summer when the growth of L. digitata slows but that of *L.. hyperborea* ceases completely (Kain, 1979). Although growth is reduced in the autumn, photosynthesis continues and consequently, there is an increase in the reserves of carbohydrates stored in the lamina (Lüning, 1979). These reserves are utilised during the late winter growth period when light levels are too low to support growth.

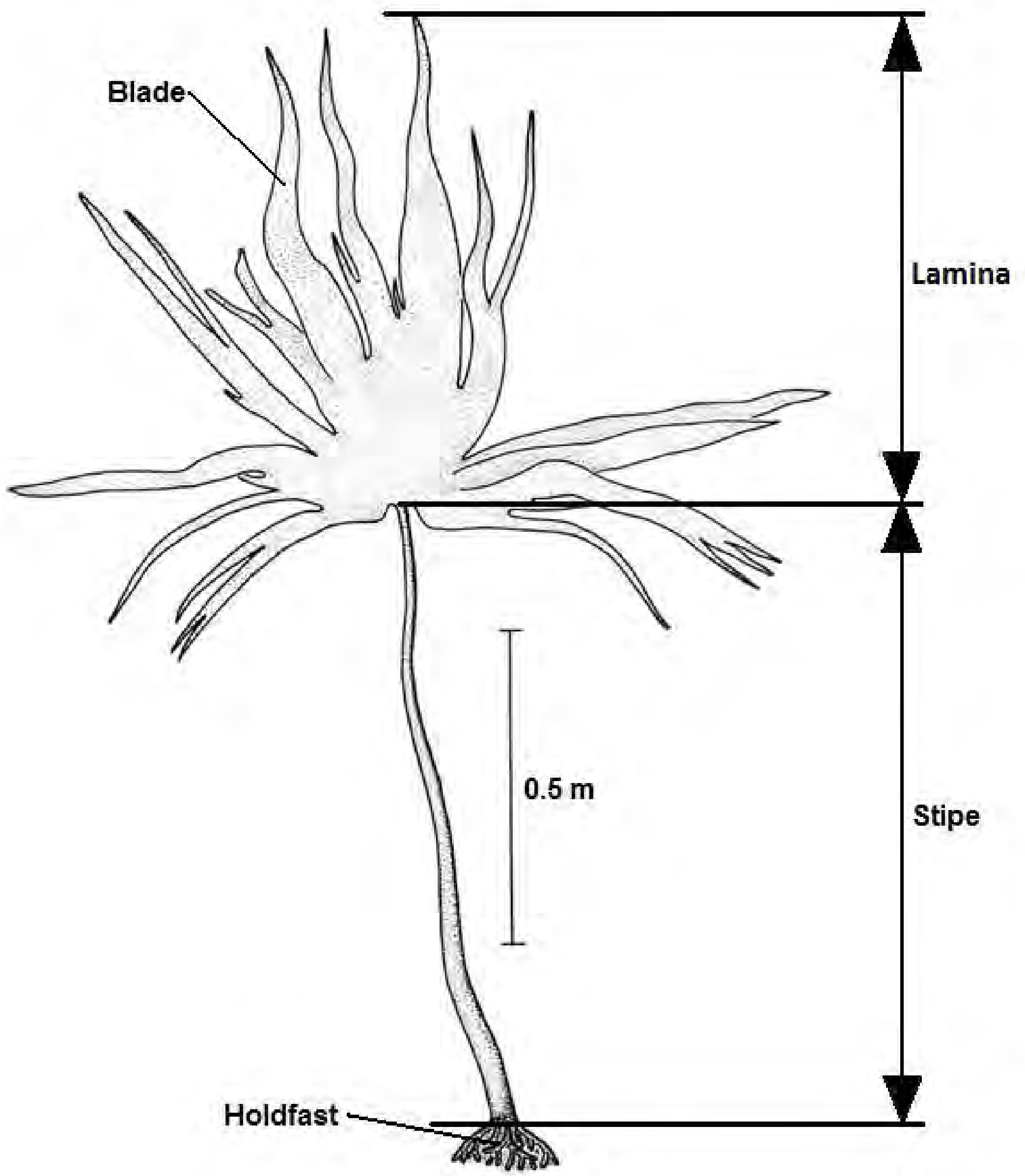

Figure 1.3: Definitions of the morphological features of *Laminaria* spp. (*Laminaria hyperborea* pictured).

2. Aims and Objectives

2.1. The Brief

The project proposal aimed to develop a practicable methodology for the quantitative assessment of the inshore kelp resource in order to facilitate the development of appropriate management plans and sustainable harvesting practices. This was to be achieved by

- developing, trialing and assessing potential methodologies for the estimation of kelp standing stock biomass at two inshore sites(one on the south-west coast and one on the west coast of Ireland);
- investigating techniques and methodologies to differentiate between the two kelp species, *Laminaria digitata* and *L.. hyperborea*; and
- carry out a series of acoustic trials to estimate kelp biomass (including appropriate ground truthing) and, where appropriate, fine-tune the methodology.

2.2. Statistical Confidence

The project was to be carried out over two summers (growth seasons) to provide verified estimates of kelp standing stock biomass from the two selected inshore sites. The project was also required to provide an assessment of the methodology in terms of its accuracy, practicability and reliability and demonstrate a robust operating procedure which generates estimates of kelp biomass to a high degree of confidence (80%). The issue of confidence was considered closely during the trial and subsequent surveys. The 80% degree of confidence may be interpreted to imply that acoustic mapping coupled with modelling can be used to predict the kelp biomass at any location. Any estimate of biomass in a biological community will have a certain margin of error. Key sources of error include, but are not limited to, calibration of the acoustic equipment, sample positioning, diver measured morphometrics and the variation associated with the testing of derived models at new sites. Every effort was made to reduce errors from these sources during field measurements. through improved accuracy or account for it during subsequent analysis through regression models, smoothing and aggregation. We have interpreted the 80% confidence required for the deliverables to be the probability of our predicted values of kelp biomass being within acceptable limits of the actual biomass (as measured during ground truthing). Here we set the limits to be within 10% of the actual values and so we aim for 80% of our predicted estimates of kelp biomass to be within this range.

2.3. Application of the Proposed Acoustic Methodology

Although this project is concerned with resource assessment and the potential development of kelp harvesting practices, the methodology being developed here can have other applications for a wide range of end users. In addition to being a significant resource, kelp beds constitute a very important habitat. Kelp provides a substrate for the attachment of many sessile species, provides a refuge from predation and acts as a nursery ground for many important fish and shellfish species. Kelp beds also alter the local physical conditions underwater by damping wave surge and affecting hydrodynamic flow (Eckman et al., 1989; Duggins et al., 1989; Steneck et al., 2002). The altered flow leads to higher rates of sediment and detritus deposition due to longer particle residence times and higher probabilities of particle redeposition beneath kelp canopies (Eckman et al., 1989). Biologically generated habitats such as kelp forests, through the provision of an altered environment, have a strong positive effect on species diversity when compared to neighbouring unvegetated areas (Bruno and Bertness, 2001 and references therein). Harvesting is likely to have wide-ranging effects on the environment and species associated with kelp, which highlights the importance of effective management practices. The technique being developed here will contribute greatly towards our understanding of the impacts of kelp harvesting. It could also offer a means of quantitative habitat assessment for the scientific and conservation communities with a view to monitoring these significant biological generated habitats. The use of this tool for habitat assessment could also be expanded to other macrophytic communities, such as seagrass beds.

2.4. Objectives – Acoustic

The primary objective of the research was to identify appropriate acoustic hardware and develop a protocol relevant to the detection of kelp biomass. Several acoustic systems were considered and evaluated as part of the project, and both swath and single beam systems were considered. The relative simplicity and ease of use of SBES makes them an ideal tool for investigating seabed or near-seabed properties and this was considered to be an important factor in the choice of system, since it is expected that the methodology to emerge from the study should be readily accessible to others and not just be available to research workers. Notwithstanding the use of swath systems offering greater coverage, the processing of the data for biomass detection and analysis of near seabed returns were not sufficiently developed to be considered for automated processing and analysis. Furthermore, it was also considered, for the same reasons, that the system adopted should be commercially available and well supported with readily available hardware and software.

Two systems lead the way in fisheries sonar and also have applications for the survey of submerged macrophytes. The first is the BioSonics DT-X Digital Echosounder System used in combination with BioSonics EcoSAVdata processing software, which provides a complete system for assessing the presence/absence of macrophytes and the density of plants (Stepnowski et al., 1996). The system has been used extensively for the mapping and assessment of macrophytes (Sabol et al., 1996; Schneider et al., 2001; Sabol and Johnston, 2001; Sabol et al., 2002). However, after discussion with BioSonics it was concluded that there was little scope for the determination of biomass using EcoSAV. It was suggested by Biosonics that their sounder would interface with another software package and this information resulted in the application of the second system.

Sonar5Pro is a software package for fisheries sonars that also includes facilities for macrophyte analysis (Balk and Lindem, 2005) and one of the designers of the package (Helge Balk, University of Oslo) provided useful assistance during the selection of equipment. Following consultation, the Simrad dual frequency fisheries sounder, the ES60, was chosen in combination with a Simrad 38/200 Combi D transducer operating at 38 kHz and 200 kHz. This is a high specification system used in fisheries and scientific research. This sounder has the advantage of using relatively light and inexpensive transducers, making the system suitable for use on small vessels in shallow water where there is a risk of damage. The Biosonics hardware, by contrast, processes most of the signal in the transducer heads resulting in the transducers being heavy and expensive to replace.

The software, Sonar5Pro, was chosen as it is possible to analyse data from a range of echo sounders and is not specific to a single manufacturer. Additionally, the software is freely available for use as a processing tool. Only conversion of the raw data to Sonar5Pro format requires a license which is commercially available. This enables the data to be exported on post data collection and then manipulated and processed at a later date without restrictive software licensing. The software is also well supported by the manufacturers who have an academic interest in the software application and who provide modifications and changes to software as technical support.

2.5. Objectives – Biological

The main objective of the diving surveys was to examine the morphological characteristics of the kelp in detail for each of the chosen survey locations. The morphometrics could then be compared with the suite of derived acoustic parameters in order to identify a meaningful relationship between two or more of these variables. A sampling protocol was devised to co-ordinate the biological sampling closely with the acoustic surveys. This sampling protocol was representative of the whole kelp bed and included both the *L.. digitata* and *L.. hyperborea* zones, and varying densities of kelp cover.

The primary focus of the project was to estimate kelp biomass directly from the acoustic signal. In order to aid this process we also examined how the morphometrics of each kelp specimen, that is the physical dimensions, related to the total biomass. This was carried out across all the surveys, and therefore across different seasons, to determine whether there were any consistent relationships. This would potentially allow indirect estimates of kelp biomass through the acoustic detection of the relevant selected physical dimensions.

A further major focus of the project was to establish the possibility of distinguishing between the two kelp species, *L.. digitata* and *L.. hyperborea*, using the acoustic equipment. The biological surveys physically distinguished between the two kelp species, particularly during the near-shore transects, and therefore allowed description of the transition from the subtidal populations of *L.. hyperborea* to the shallow subtidal/intertidal populations of *L.. digitata*. Additional surveys were also carried out to examine the depth profile of the kelp at the inshore survey sites to determine the lower limit of their distribution.

Finally, the biological surveys examined the growth rates of *L.. hyperborea* at the two sites in the south-west of Ireland. Growth rates were monitored every three months for the duration of the project to confirm seasonal changes and identify any differences between exposed and sheltered locations.

2.6. Strategy – Surveys

Following the pilot survey in Northern Ireland, which trialled the acoustic equipment and survey protocol, three surveys in the south-west of Ireland and a final survey on the west coast of Ireland were completed. During the surveys, emphasis was placed on fully integrating the acoustic surveys with the biological sampling through the use of the Differential Global Positioning System (dGPS) and strict operating procedures. The strict operating procedures also helped minimise observational error throughout the project. Enough data was collected to ensure statistical robustness for any analysis and model construction.

Two sites were scheduled for examination in each of the three survey areas: the pilot, south-west and west coast surveys. In each survey area, the sites varied slightly in their topography; one being gently sloping and the other relatively level. For the south-west and west coast surveys, the sites were also selected to vary in their exposure. The exposure category assigned to each site was determined by the prevailing weather conditions for the area. In the south-west survey area, the prevailing winds are south westerly, thus one site was selected with a north east aspect (sheltered) and one was selected with a south-west aspect (exposed). The west coast survey area was characterised by prevailing winds from the west and so one site was selected with an east facing aspect (sheltered) and one with a south-west aspect (exposed). This variation allowed the surveys to examine the biomass in kelp beds growing under different environmental conditions.

The three surveys in the south-west area were conducted in autumn 2008, spring 2009 and summer 2009. The survey times were selected in relation to the main growth season for kelp, which runs from January to June or July, such that the surveys were outside, during and at the end of the growth season, respectively. A comparison of the different surveys provided an indication of the seasonal variation in biomass within the kelp beds. The final survey on the west coast was conducted in spring 2010 and used to validate the models developed on the basis of the south-west surveys to estimate the biomass in the kelp beds from the acoustic data. These estimates were then verified by further biological sampling. The west coast survey was compared to the survey from the south-west in spring 2009 as a seasonal equivalent from a different location.

3. Methods

3.1. General Methods

3.1.1. Survey Locations

The project set out to develop and trial an acoustic methodology for the detection and estimation of kelp standing stock before assessing the technique at two inshore locations on the Irish coast. A trial survey was carried out in Northern Ireland near the Queen's University Belfast Marine Laboratory at Portaferry, Co. Down on 18-22 August 2008 (Figure 3.1). The two inshore locations for the three main surveys based on the south-west of Ireland were selected near to Baltimore in County Cork (Figure 3.2). The west coast survey was based on the approaches to Killary Harbour in County Galway (Figure 3.3). The three south-west coast surveys were carried out on 12-25 October 2008 (SW1), 25 April - 7 May 2009 (SW2) and 7-20 August 2009 (SW3). The final major survey, on the west coast, was carried out on 15-26 March 2010 (W1). The two sites selected in each survey area were; Site A (level) and Site B (sloping) in the pilot survey (Figure 3.1), Slip Site (sheltered, sloping) and Calf Site (exposed, level) in the south-west survey (Figure 3.2) and Crump Site (Sheltered, level) and Inishdegil Site (exposed, sloping) in the west coast survey (Figure 3.3). Each of the sites was initially surveyed to collect bathymetric and sidescan sonar data using the GeoSwath Plus interferometric multibeam system connected to dGPS for accurate positioning. The GeoSwath Plus data were used to determine substrate types and also served as useful base maps for the subsequent single beam surveys. The acoustic method under development for this project used a Simrad ES60 Echosounder and software, also linked to dGPS for accurate positioning. The Simrad ES60 was used to scan each site, ensuring good coverage, at dual frequencies (38 and 200 kHz). Following the acoustic survey of the kelp beds, divers were used to ground truth the data through sampling and surveys.

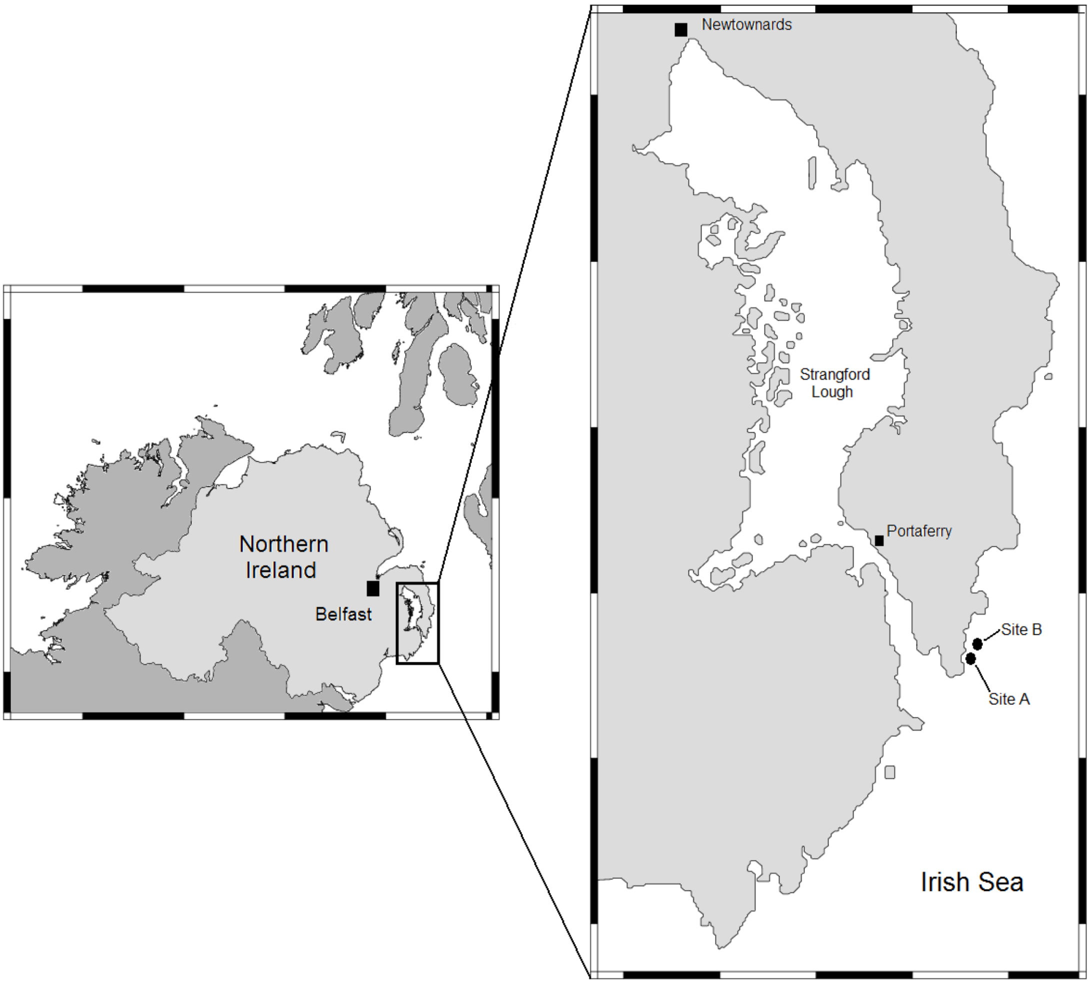

Figure 3.1: Location of the trial survey sites (A & B) in Northern Ireland.

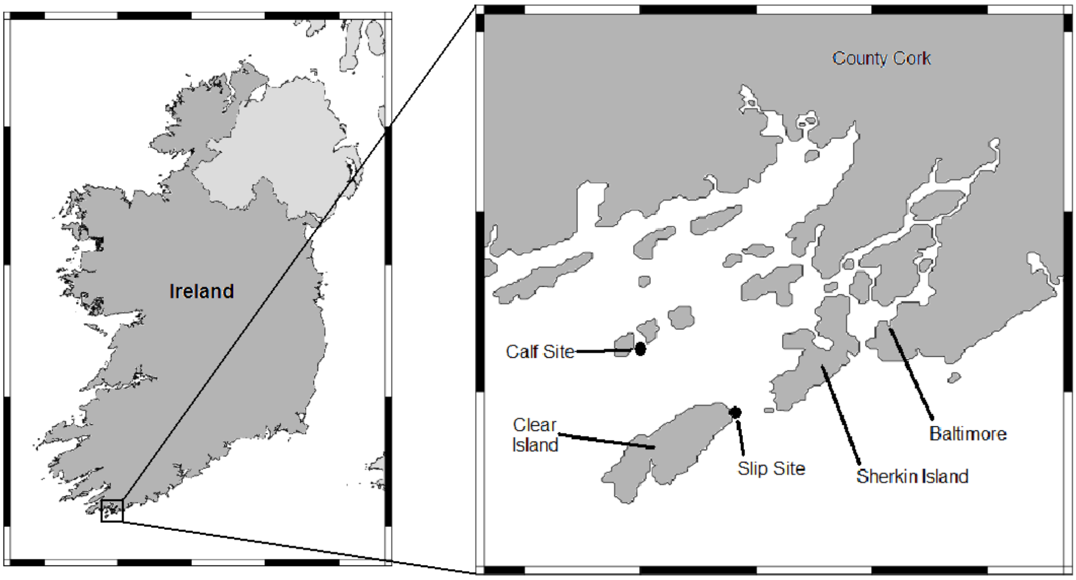

Figure 3.2: Location of the south-west coast survey sites: Calf (exposed) & Slip (sheltered), in County Cork.

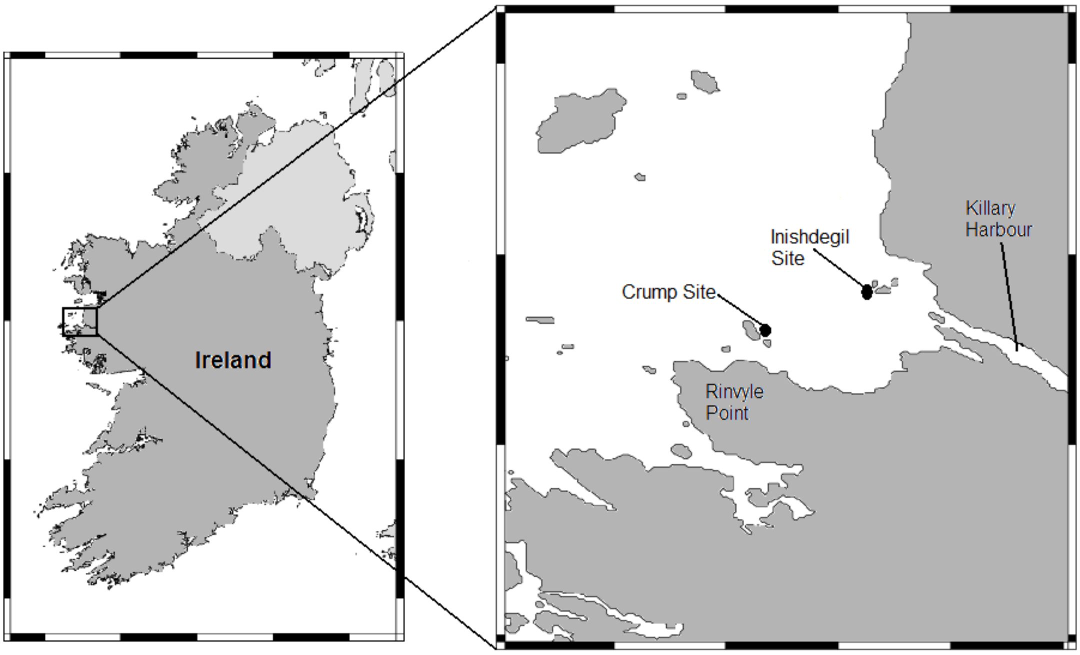

Figure 3.3: Location of the west coast survey sites; Crump (sheltered) & Inishdegil (exposed), in County Galway.

3.1.2. Acoustic Surveys

Equipment set up and deployment

The Simrad system consists of a transceiver unit (the General Purpose Transceiver – GPT), the Simrad 38/200 Combi D transducers and the ES60 fish finding sonar capture software (Figure 3.4). The ES60 is software that, once installed on a laptop computer, will interface with the transceiver and act as the echosounder. The full echogram can be recorded and played back for inspection and also exported to third party software (Sonar5Pro) for analysis.

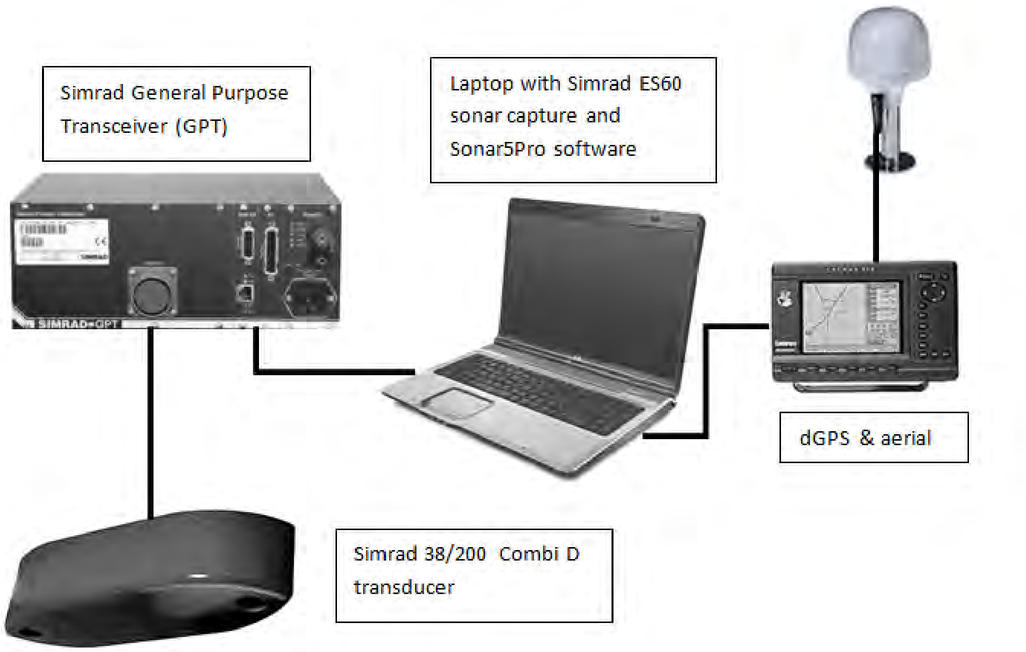

Figure 3.4: Layout of the fisheries SONAR.

The 'ping' rate was set to maximum and pulse duration set to minimum (0.256ms) to give the highest possible vertical resolution. The transducer is designed to be fixed to the hull of a ship. However, in this project, the transducer was mounted on a bracket on the end of a pole that could be attached to the side of the survey vessel. This was necessary so that the system could be deployed from different vessels. To comply with the manufacturer's recommended set-up:

- the bracket was angled slightly relative to the pole so that the transducer tilted forwards;
- care was taken to align the transducer parallel to the long axis of the vessel using straps running fore and aft; and
- the transducer was positioned 1m below the surface of the water to reduce the likelihood of effects arising from aeration.

The full echogram was recorded by the ES60 together with differentially corrected GPS so that the echograms were georeferenced. The echograms were played back through Sonar5Pro, which detects the seafloor and the top of the vegetation and measures the echo intensity between these two horizons. The program also makes use of echoes from a number of consecutive 'pings' to estimate the percentage area inhabited by algae and the percentage volume inhabited. In summary, the Sonar5Pro measurement outputs were:

- Depth of seafloor
- Height of kelp above the seafloor (bio height)

- Signal strength between the seafloor and top of the kelp canopy
- Percentage area inhabited (PAI)
- Percentage volume inhabited (PVI)

The program is designed to detect the depths of seafloor and canopy automatically. However, other factors, such as aeration, shoals of fish and plankton may affect the echo and confuse the automatic process such that some manual correction of the tracking or editing of the final data set is required to ensure that spurious measurements are avoided. A typical echogram from the kelp survey is shown in Figure 3.5 which illustrates the various components of the echogram and the results from auto-detection of the canopy and seafloor.

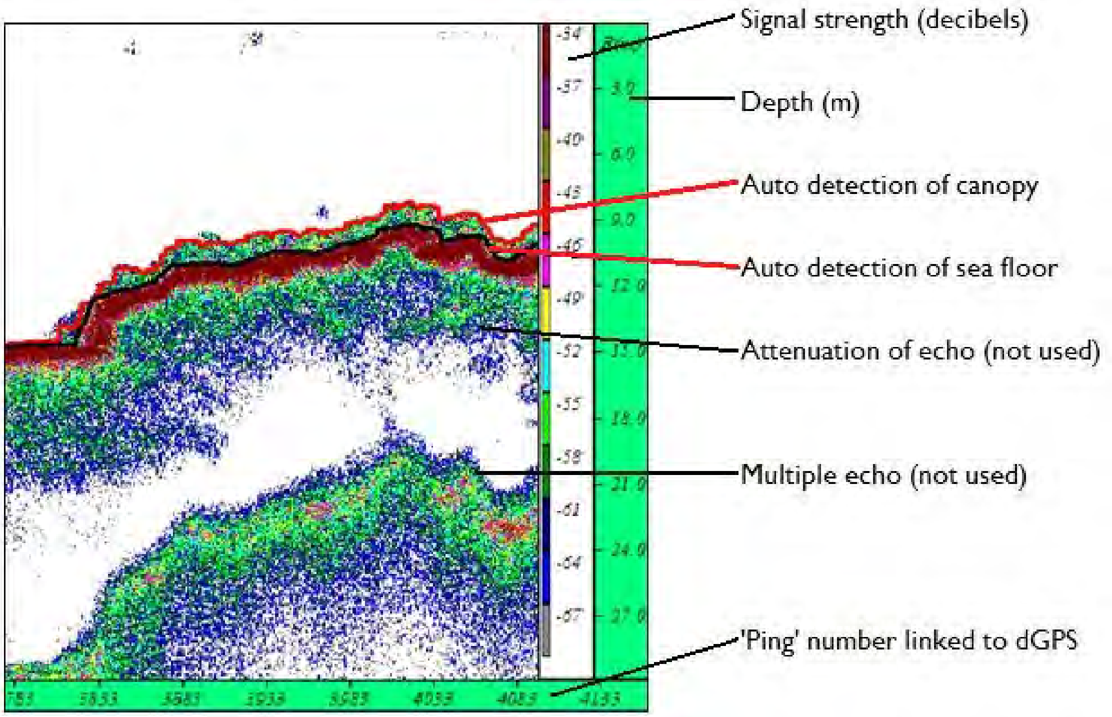

Figure 3.5: Echogram illustrating main features and auto-detection.

A GeoSwath Plus Interferometric (GeoAcoustics) system was used for high resolution bathymetric surveys. This system provided bathymetric data which were geographically coincident and corrected for tide, vessel movement and position. The data were also corrected for distortion caused by variations in the speed of sound through water and sound velocity profiles were taken at intervals through the survey using an Odum SVP transducer. The system was calibrated when first set up on the vessel and cross tracks were collected during the survey for quality control to ensure data consistency. There was 100% overlap between the swaths.

The swath bathymetric data were processed to create an XYZ grid of water depth with a resolution of 0.5m. The grids were imported into Surfer, a 3-D surface modelling software package, in which sun-illuminated digital elevation models (DEMs) were created. Images from these models were exported as geotiffs which could then be imported into the GIS project. Swath bathymetry of the south-west sites are shown in Figures 3.6 and 3.7.

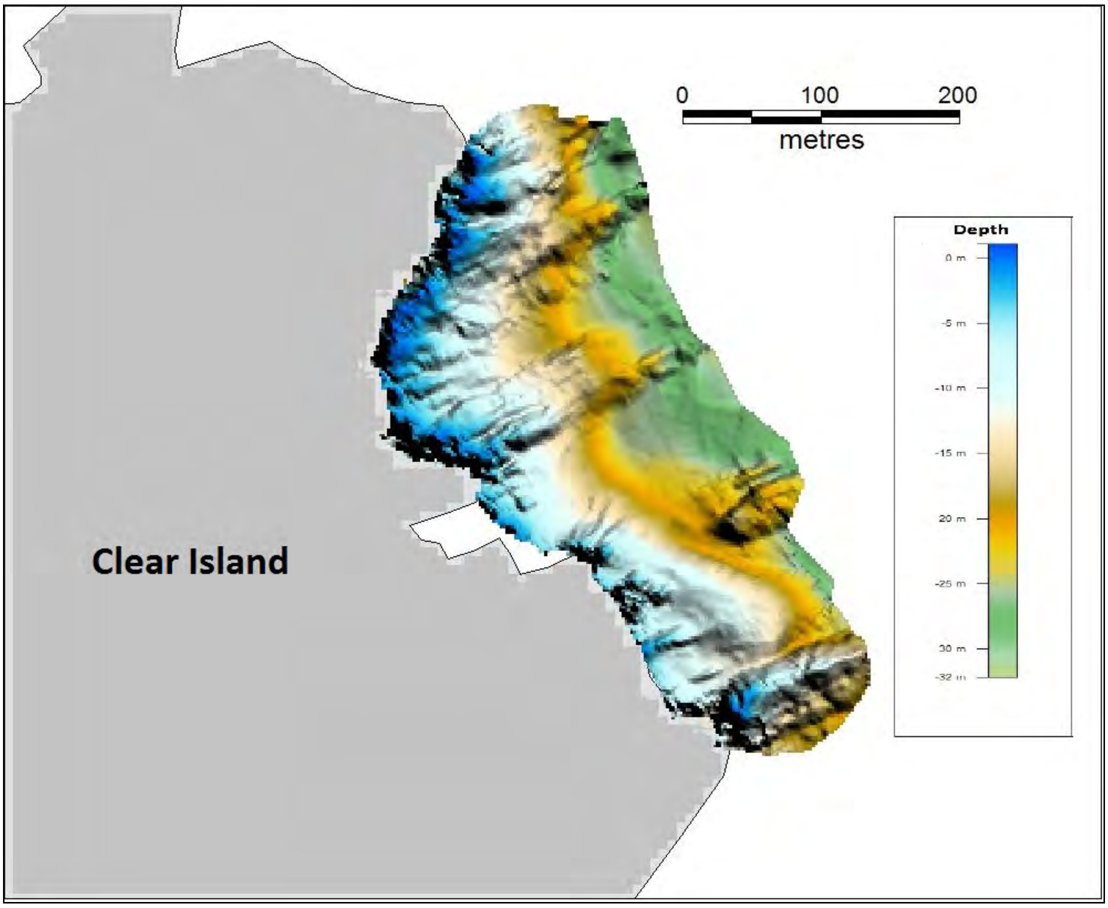

Figure 3.6: Swath bathymetry of the Slip site (sheltered) in the south-west survey

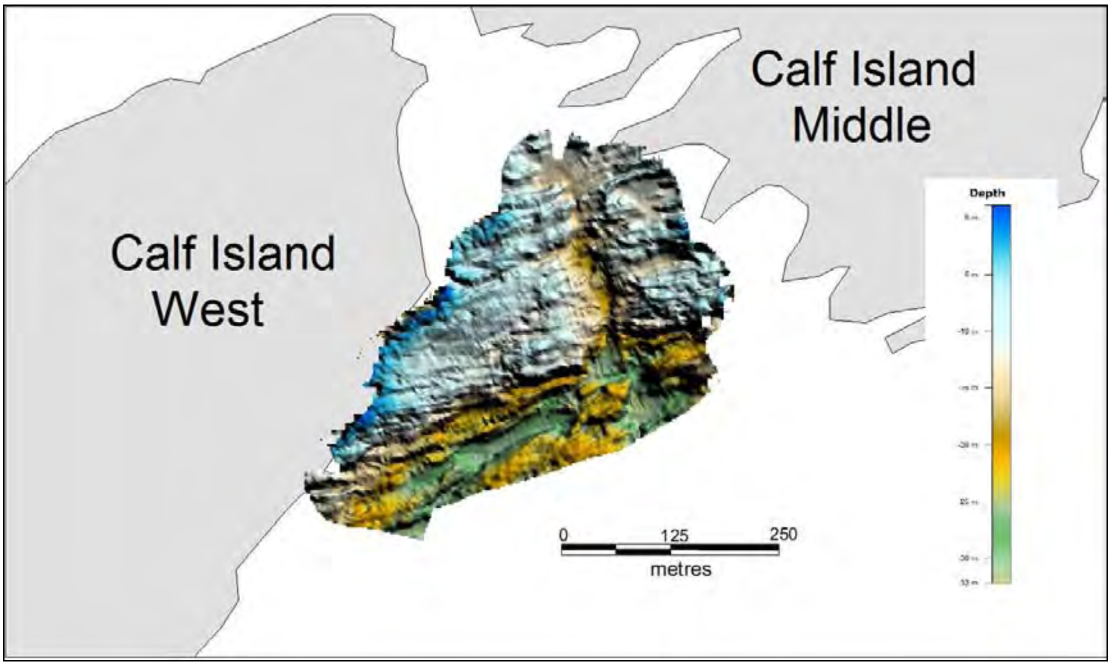

Figure 3.7: Swath bathymetry of the Calf site (exposed) in the south-west survey.

Survey methodology

The purpose of the survey was to test the ability of the single beam fisheries sounder to detect and map the extent of kelp, to measure kelp height and estimate kelp biomass. Many environmental factors influence the distribution of kelp and this project focussed on the relationship with depth at exposed and sheltered sites at different times of the year. The nature of the seafloor (substratum and topography) might also be expected to affect kelp distribution and each site was surveyed using a swath bathymetric system (described above) to provide a detailed image of the seafloor as context for interpreting the results of the surveys. The acoustic track data were accumulated as the vessel systematically criss-crossed the sites. Survey tracks were evenly spaced with two layers running perpendicular to each other. The ES60 recorded each 'ping', but the dGPS updated only every 10 measurements. Thus, the data consist of about 10 measurements at a single point with consecutive points separated by 1.5-2.5m depending on vessel speed.

The outputs from Sonar5Pro were calibrated against the measurements of the kelp made by the diving team at specific locations. Potentially, variability in the data could be caused by positioning errors resulting in a slight mismatch between the acoustic data and the ground truth samples. Geotagging the acoustic data could have an inherent positional uncertainty of up to 3m (due to dGPS error and the effect of the lag between recording the acoustic data and the dGPS update rate). Placing the divers on the right location relative to the acoustic data is similarly susceptible to positional error. Thus, although the survey team improved their ability to place divers close to the desired acoustic records, there remained a degree of uncertainty about the correspondence between the acoustic data and the ground truth measurements, which could be misaligned by up to 3m.

The number of observations made by divers was between 10 and 12 per site per survey. Additional data on kelp height was obtained using a drop-down bullet video camera and depth sensor. However, no biomass data were available from these samples.

3.1.3. Biological Sampling and Surveys

Field Sampling

Sample locations were selected within the known kelp zone at each site by Envision Ltd. to correspond with the maximum amount of acoustic data. This meant pinpointing the intersections of the survey tracks which contained the highest number of acoustic 'pings'. Ten locations were sampled at each site in the pilot and the first of the south-west surveys (SW1). This was increased to 12 sample locations for all the subsequent surveys to ensure good coverage for each of the sites. Sampling locations were positioned using dGPS to ensure highly accurate correspondence between the acoustic data and the biological sampling. The sample locations varied in depth to cover the full extent of the kelp zone and therefore a wide range of densities and biomass. Each location was sampled through the use of SCUBA where all kelp were collected from a circular area of 1m radius (3.14 m^2) and then brought to the surface for full morphometric analysis. The morphological measurements recorded for each kelp specimen are listed in Table 3.1. Definitions of the kelp morphological terminology can be found in Figure 1.3. The full morphometrics were recorded immediately on return to shore to prevent any degradation of the kelp material.

Table 3.1: Morphological measurements recorded for each *Laminaria* specimen.

Characteristic	Units	Method/Description
Stipe Length	cm (1 decimal place)	Distance from base of stipe to tip of stipe.
Stipe Diameter	mm (1 d.p.)	Diameter at halfway point of the stipe.
Stipe Mass	g (2 d.p.)	Weighed on a balance
Maximum lamina/blade length	cm (1 d.p.)	Distance from base of lamina to tip of the longest blade.
Thickness of blade base	mm (3 d.p.)	Thickness at the base of a blade, but not at the meristem, within 1cm of the edge.
Thickness of blade end	mm (3 d.p.)	Thickness at the end of a blade, in the centre of a blade, within 1 cm of the edge
Lamina Mass	g (2 d.p.)	Weighed on a balance

For each day of the acoustic and diving surveys, light measurements were taken (Skye Instruments SKP 2200 PAR Quantum, 2 channel sensor) to determine the percentage of surface irradiance that was reaching the depths occupied by kelp plants. Readings were taken at 1m depth intervals down to a maximum of 19m. Although the readings were only made over a short period, they provided a representation of the light environment experienced by the kelp in the surveys. In addition to light readings, spot surveys were also carried out to examine the depth profile of the kelp at the survey sites to determine the lower limit of their distribution. Spot surveys were also conducted in more offshore locations to determine the lower limits of distribution in clearer water.

Transect Surveys

The transition zone between the two species of kelp, *L.. digitata* (low intertidal/shallow subtidal) and *L.. hyperborea* (shallow subtidal into deeper water), was determined using diving surveys which were conducted during spring high tides and corresponded with areas of concentrated acoustic data. The survey transects started at a depth of 6m (well inside the *L.. hyperborea* zone) and ran perpendicular into the shore, ending in the intertidal zone. Quadrats (0.25 m^2) were placed at 1m vertical intervals until a final depth of 1m was reached. The species of kelp, number and size of each specimen were recorded for each quadrat, as well as the time of sampling so that the sample depth could be related to chart datum. Three transects were carried out for each site and for every survey, except for the trial survey in Northern Ireland.

Growth Rate of Laminaria hyperborea

The growth rate of *L.. hyperborea* was determined by marking 40 kelp specimens at each of the sites at the beginning of the first south-west survey. The tagged kelp were then logged and re-measured every three to four months to determine their growth rate and the level of loss in the population for the duration of the project. Growth rate was determined by measuring the length of the stipe at each visit and also by using the 'punched hole' technique of Parke (1948) for growth in the lamina.

3.2. Statistical Methods

3.2.1. Regression Analysis

Linear regression analysis was used to construct models of the linear relationship between the direct/derived acoustic measurements on each of the south-west coast surveys and the actual kelp biomass as measured through diver ground truthing. These models were then applied to the west coast survey acoustic data to predict kelp biomass in this location. The predicted values were then compared to the actual values from diver surveys to test the accuracy of the models.

3.2.2. Spatial Interpolation and Distribution of Biomass

The relationships between the acoustic values (mainly PVI and bio height) and biomass were applied spatially to estimate biomass distribution and likely total biomass within a given area. Development of the regression equations was the initial step on the route to achieve estimates of kelp biomass. In order to apply the equations spatially, the acoustic data, which consisted of a series of point records along the vessel's tracks, had to be interpolated to create a continuous coverage of PVI or bio height. The regression equations were then applied to these full coverage maps to show biomass distribution.

Interpolation of the PVI values was performed using the software Vertical Mapper, which is an application designed to be used with MapInfo. A simple inverse-distance interpolation was used. The gridded values were then contoured to create polygons bounded by an upper and lower contour value. The intermediate values between the upper and lower PVI contours were calculated and the regression equations used to transform the PVI to biomass values. A thematic map was then created based on the polygon biomass values.

It should be noted that one of the effects of interpolation is to spatially smooth the data. It is important that the parameters set for interpolation (particularly the radius used to select data for value estimation) do not over-smooth the data. The radius chosen was 30m and weighting was inverse distance to the power of two. This degree of spatial smoothing eliminated spurious variation.

4. RESULTS

4.1. Biological Characteristics and Properties

Although the acoustic surveys and biological sampling covered the full depth range and therefore densities of the kelp bed, much of the analysis presented hereafter refers to data from the 'closed canopy', that is an established kelp bed within the optimum light range for growth that overshadows the substrate. The closed canopy represents the bulk of a healthy bed and excludes only the small transition zone (a change of 2-3m in depth) from closed canopy to the bare substrate beyond the lower limits of the kelp. The analysis does not distinguish between the two species of kelp, *L.. digitata* and *L.. hyperborea*, at this stage and so represents a view of the kelp bed as a whole.

4.1.1. Kelp Biomass and Density

There was no significant difference in the mean biomass of kelp between the two south-west survey sites, 'Slip' (sheltered) and 'Calf' (exposed), for each of the three surveys (Figure 4.1). However, a significant difference was observed between seasons, with a lower kelp biomass in the April 2009 survey (SW2) but no difference between the October 2008 (SW1) and August 2009 (SW3) surveys (Figure 4.1). There was no significant difference in the kelp biomass between the two survey sites, which may have corresponded to the different levels of exposure at the two sites However, there was a significant difference in the kelp density, particularly for the October 2008 and April 2009 surveys when the Calf site had a higher density that the Slip site (Figure 4.2). The density differences were driven by the higher number of juvenile plants (specimens with a stipe length less than 30cm) found during these surveys (Figure 4.3). These density differences had disappeared by the August 2009 survey, subsequent to the main growth season which runs from January to June or July each year (Figure 4.2).

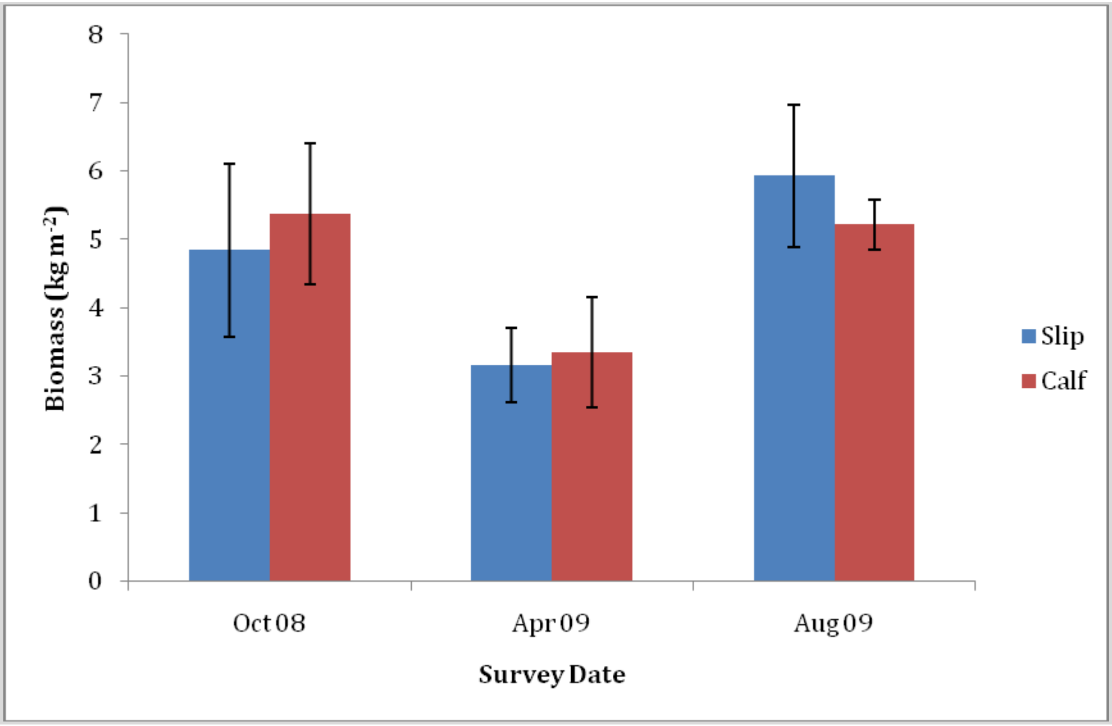

Figure 4.1 Mean kelp biomass (with standard error) at the two south-west survey sites for each of the three seasonal surveys.

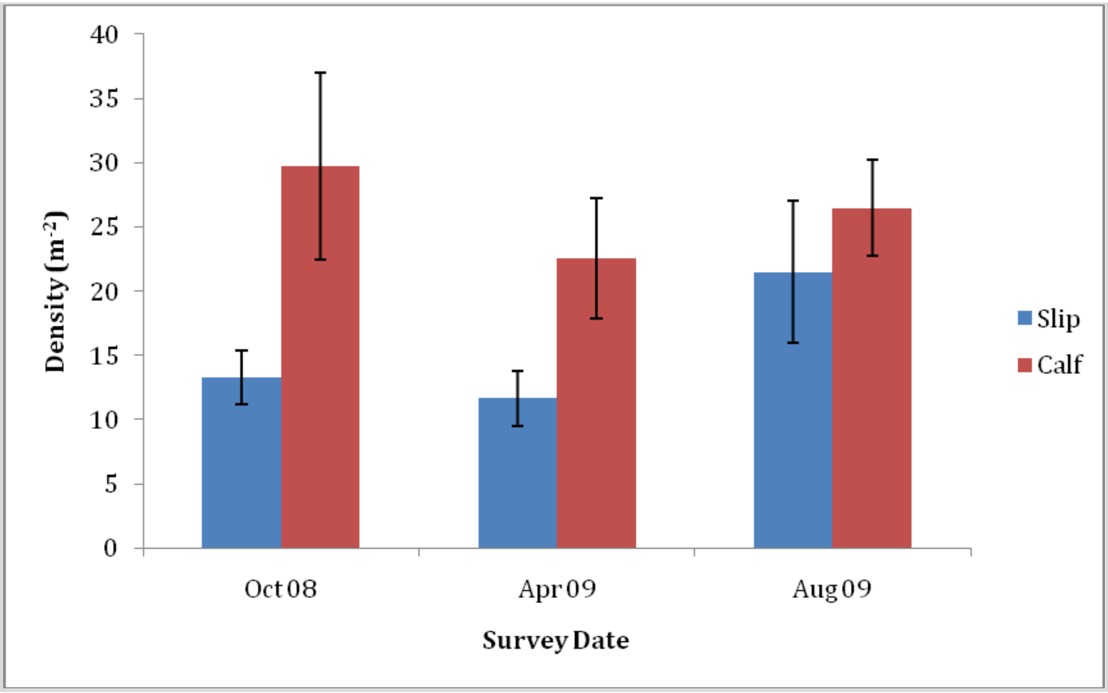

Figure 4.2 Mean kelp density (with standard error) at the two south-west survey sites for each of the three seasonal surveys.

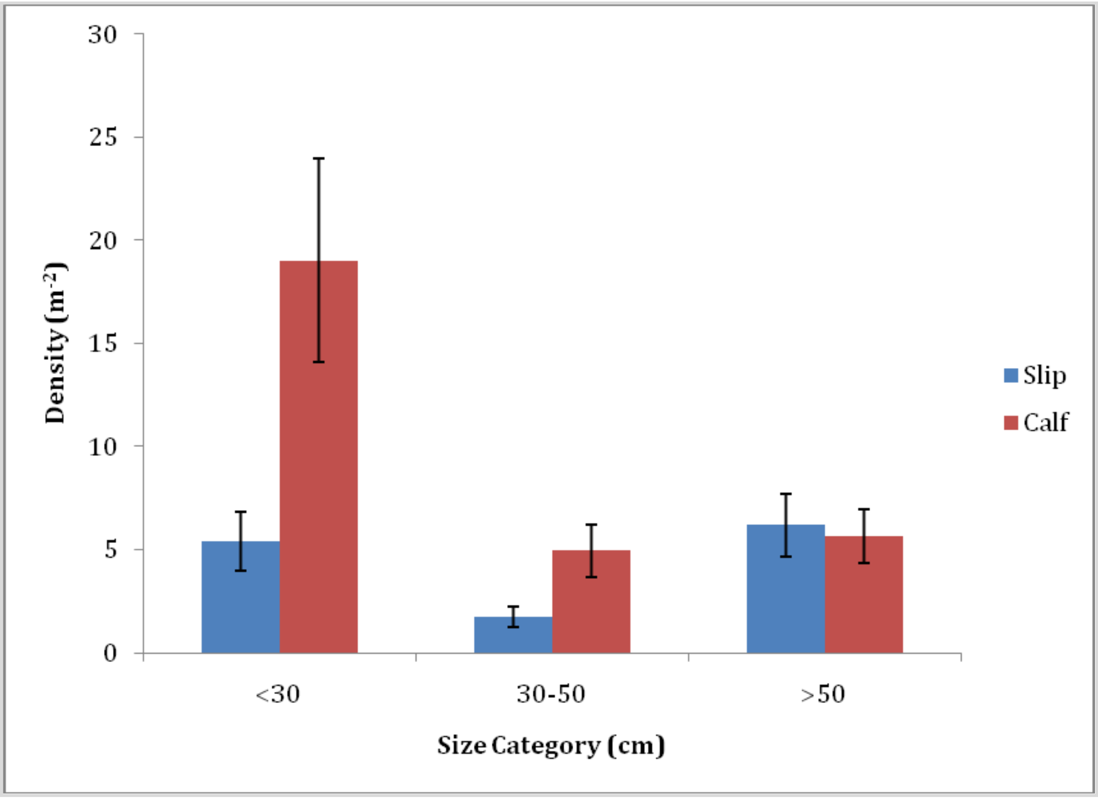

Figure 4.3 Mean kelp density (with standard error) in each size category (by stipe length) for the October 2008 survey (SW1).

There was no significant difference in the mean kelp biomass between the two west coast (W1) survey sites, 'Crump' (sheltered) and 'Inishdegil' (exposed) (Figure 4.4). This is consistent with the south-west surveys which also showed no difference in kelp biomass between the sites with the two exposures. However, the west coast survey showed a significantly higher mean kelp biomass when compared to the same exposure and time of year for the south-west survey (Figure 4.1 Apr 09 and Figure 4.4). Mean kelp density was also consistent with the south-west surveys, showing a significant difference between the two sites, which again could be related to different degrees of physical exposure (Figure 4.5). The density differences on the west coast were again driven by the higher number of juvenile plants (specimens with a stipe length less than 30cm) found during the survey (Fig. 4.6). Similar to mean biomass, kelp density on the west coast was higher when compared to the same exposure and time of year as for the south-west survey (Figure 4.2 Apr 09 and Figure 4.5).

The lower boundary of the kelp beds was consistent across all south-west and west coast survey sites. Provided there was suitable rocky substrate, kelp was found in closed canopy beds down to a depth of approximately 12-13m and were absent below 17-19m. At the time of the surveys the depth limit of the closed canopy was receiving between 2-4% of the surface irradiance and the kelp were absent at depths which received less than 1.5% of the surface irradiance. The depth distribution is known to vary with the clarity of the water (Kain, 1979) as kelp were found in closed canopies down to 20m in more offshore locations.

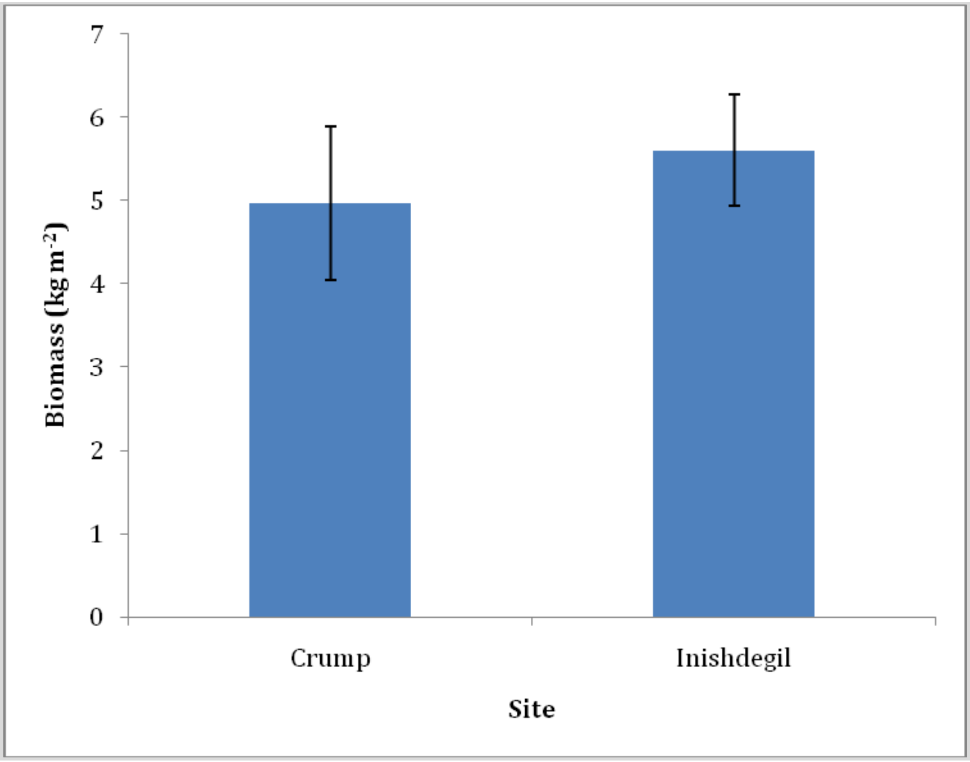

Figure 4.4 Mean kelp biomass (with standard error) at the two west coast survey (W1) sites: Crump (sheltered) and Inishdegil (exposed), March 2010.

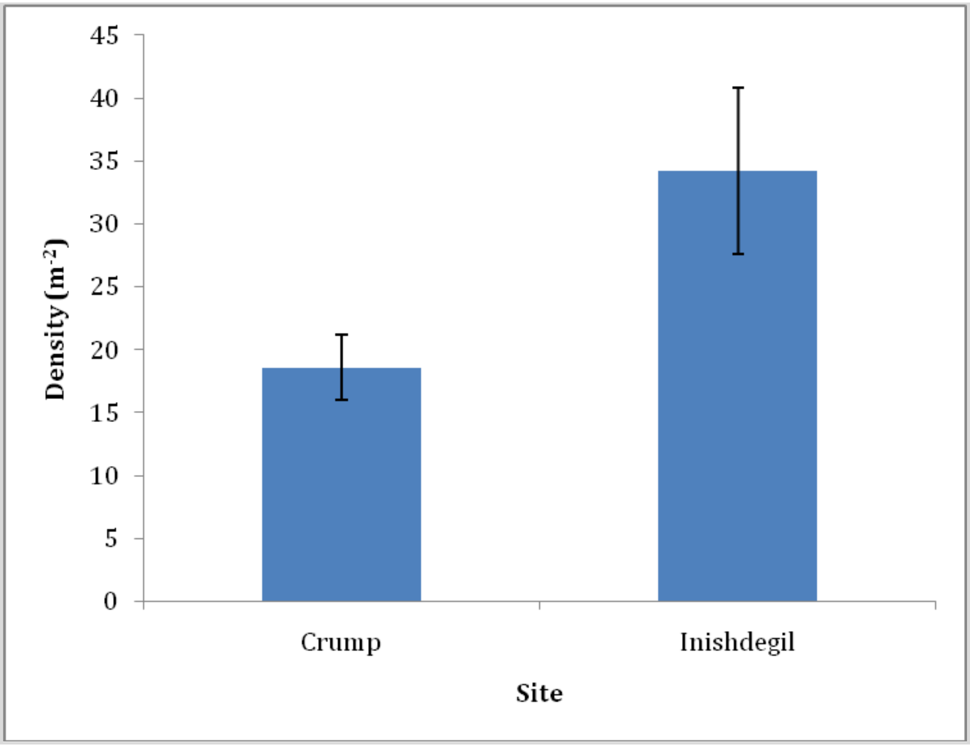

Figure 4.5 Mean kelp density (with standard error) at the two west coast survey (W1) sites: Crump (sheltered) and Inishdegil (exposed), March 2010.

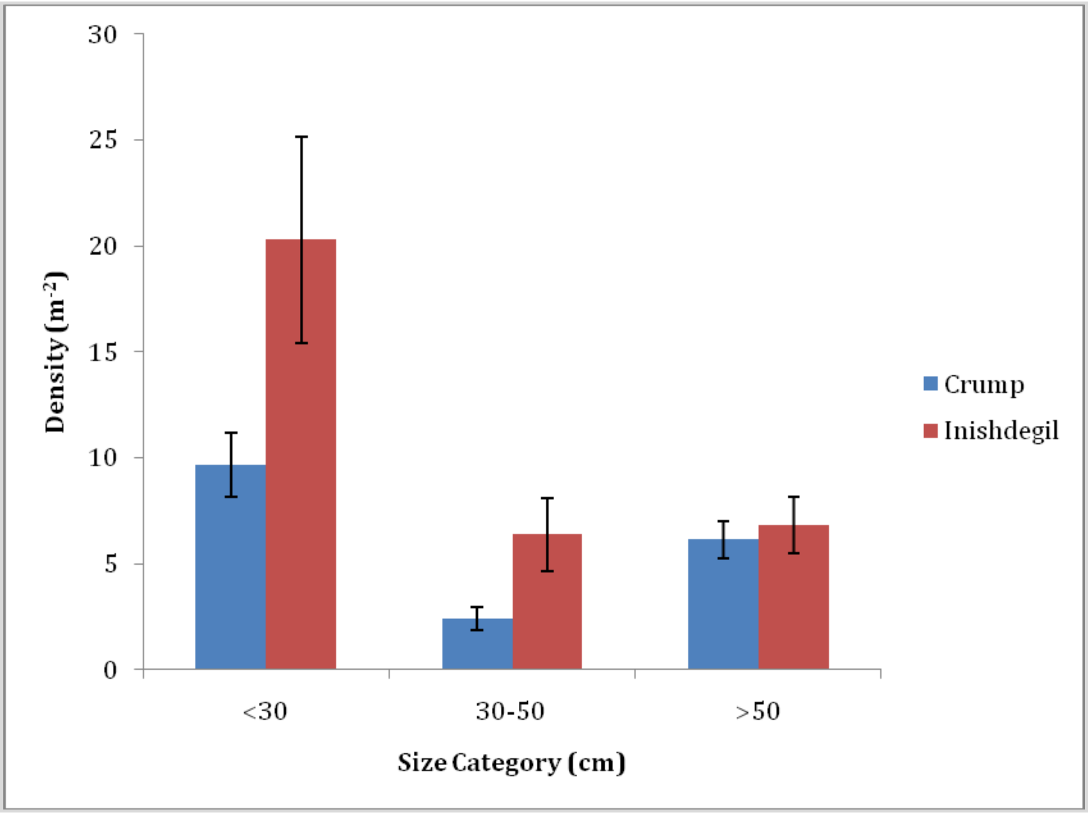

Figure 4.6 Mean kelp density (with standard error) in each size category (by stipe length) for the west coast survey (W1); Crump (sheltered) and Inishdegil (exposed), March 2010.

4.1.2. Relationships between Morphological Properties and Biomass

Examination of the morphological characteristics of kelp obtained from the two south-west sites, particularly *L.. hyperborea*, showed a consistent relationship between the stipe length of individual specimens and their total biomass (stipe and lamina mass). The data for the two sites were log transformed and showed a strong positive linear relationship between stipe length and total biomass (r^2 between 74-85%; Figure 4.7). Similar relationships were observed at both sites (exposures) and across all seasons. The west coast survey also demonstrated a corresponding relationship across both sites (exposures), consistent with the south-west surveys (Figure 4.8).

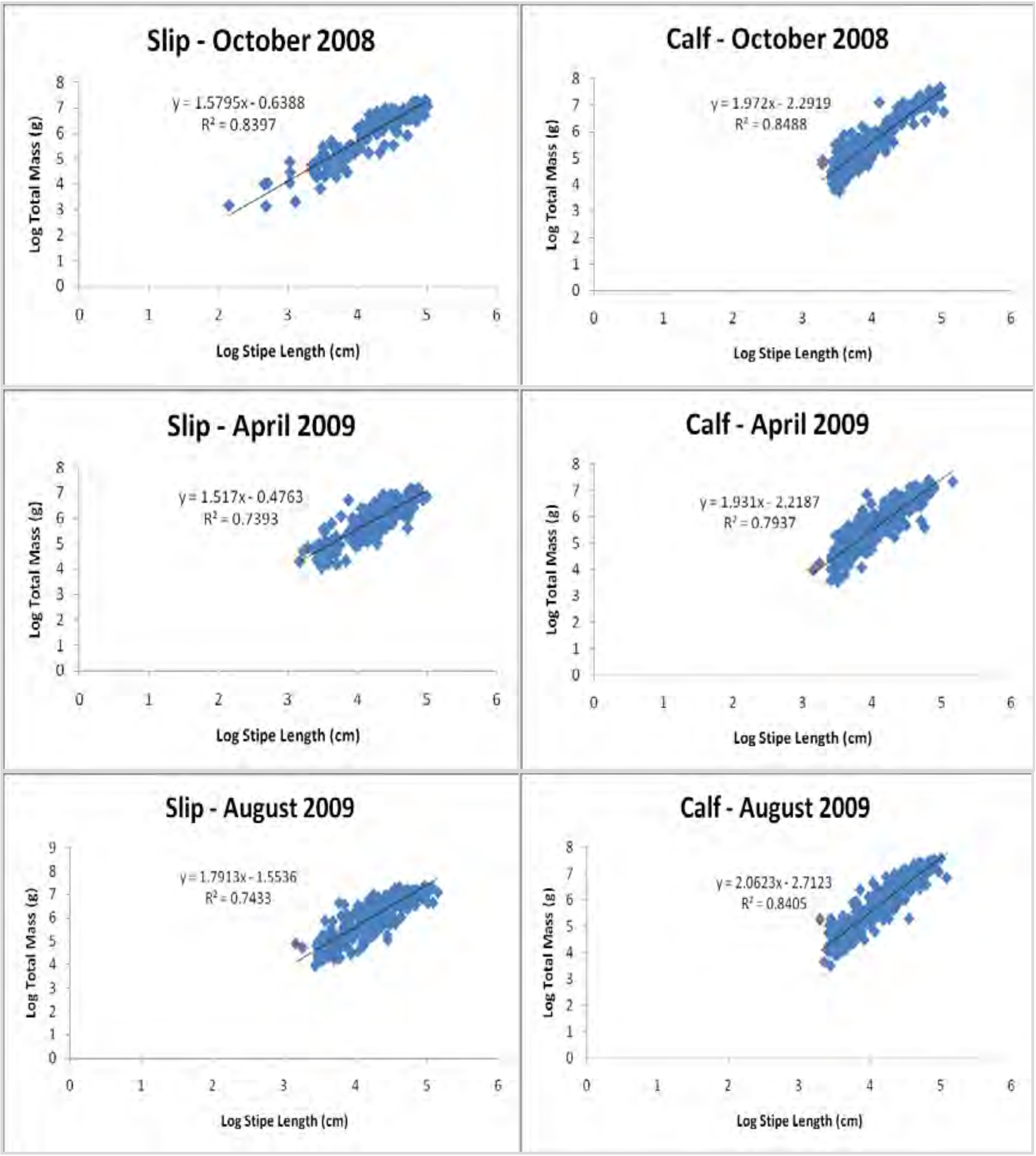

Figure 4.7 Relationship between total mass and stipe length in *L. hyperborea* for the three south-west surveys in County Cork.

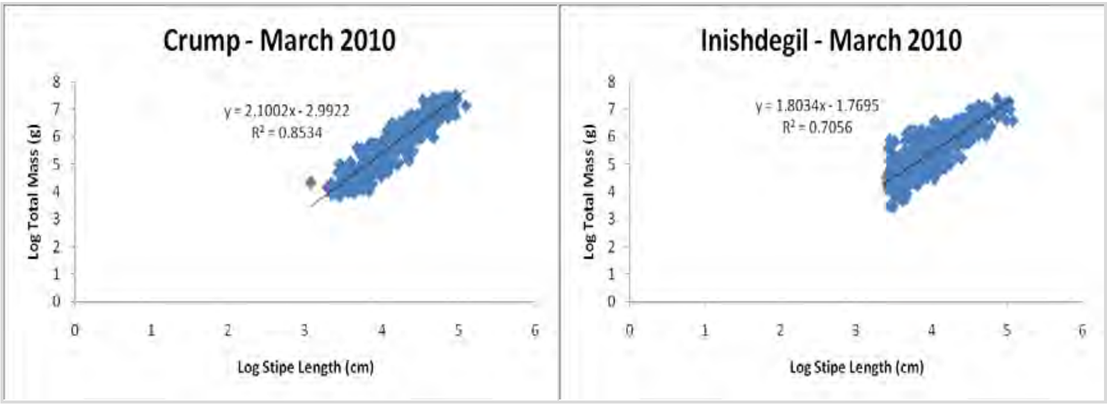

Figure 4.8 Relationship between total mass and stipe length in *L.. hyperborea* for the west coast survey in County Galway.

4.2. Acoustics Surveys

4.2.1. Comparison of Low and High Frequency Acoustic Data

Data obtained from the two frequencies (38 kHz and 200 kHz) used for the surveys were compared and it was apparent that the echogram for the 200 kHz channel was much cleaner (less backscatter in the water column) than that for the lower frequency (Figure 4.9). This resulted in a clearer definition of the seafloor and canopy from the higher frequency recorded. For this reason, the data from the higher frequency channel have been chosen to illustrate the performance of the fisheries sounder.

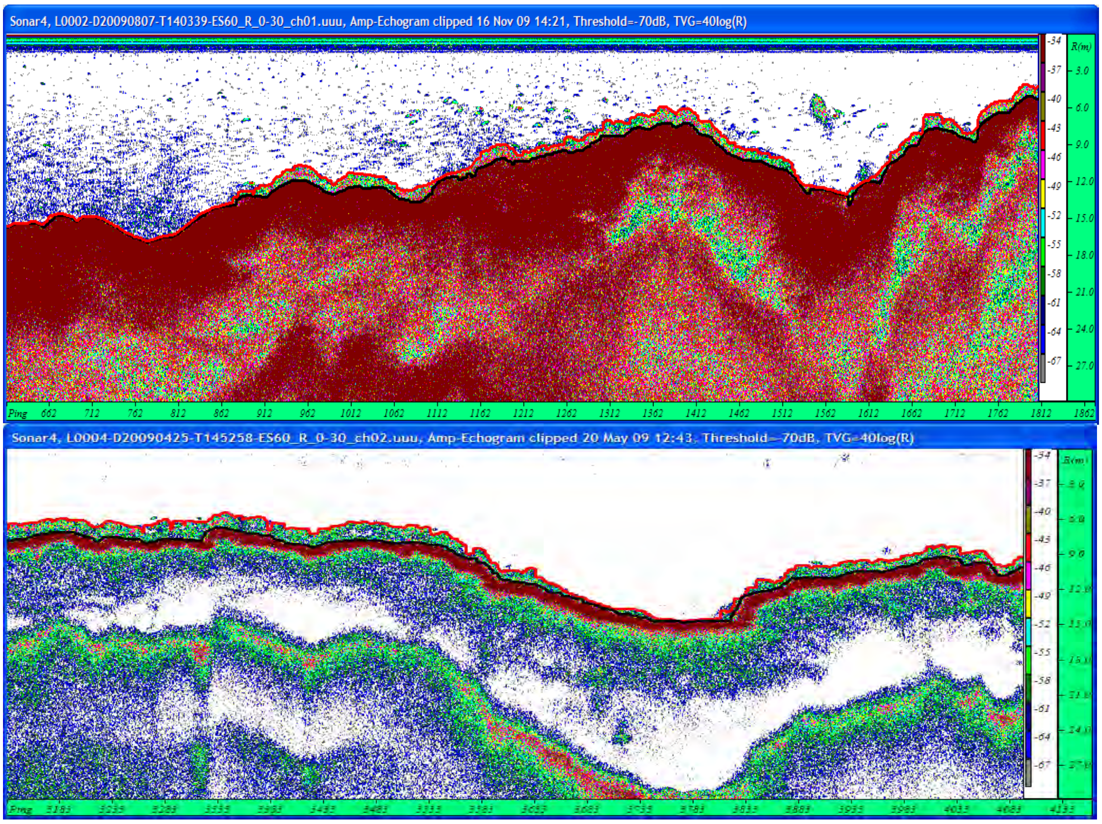

Figure 4.9: Echograms from (top) Channel 1 (38kHz) and (bottom) Channel 2 (200kHz).

4.2.2. Variability in the Acoustic Measurements

Signals detected from echo sounders are variable from 'ping to ping' and it would be expected that the measurements taken from the echogram would also be variable. The measurements taken from each 'ping' between GPS updates (there were approximately 10 such measurements between GPS updates) were examined from areas of dense kelp and it was observed that the individual measurements varied by about 20% of the mean value. Using the means smoothes out this variability and gives more stability to the measurements and these have been used for all tests of correspondence between the acoustic parameters and the ground truth samples.

Steep slopes and very rugged topography are known to affect acoustic echo responses and this was found to be the case with the measurements extracted from the echograms (Figure 4.10). Rugged surfaces can increase the duration of the signal from reverberation and scattering (von Szalay and McConnaughey, 2002) which, in the present study, resulted in an apparent increase in bio height.

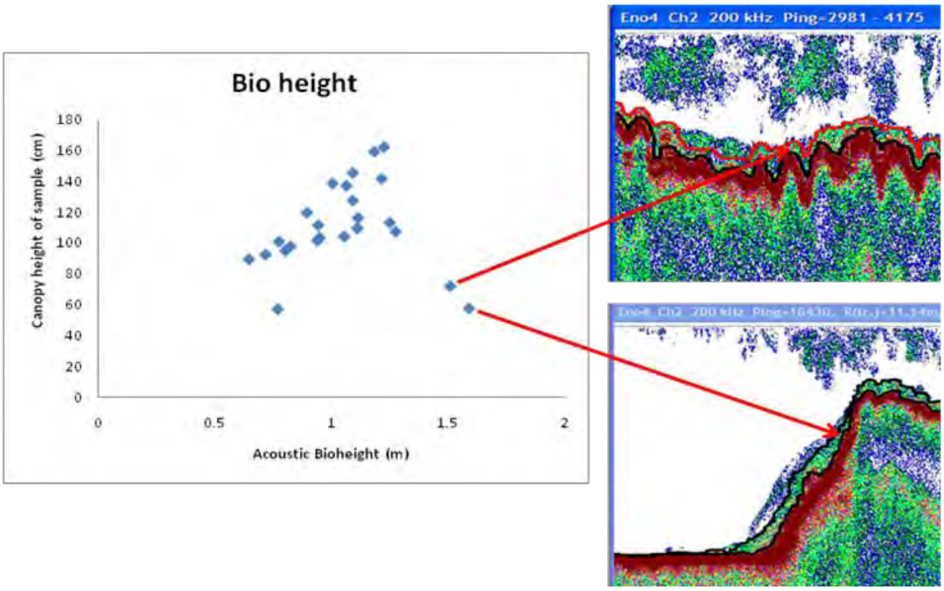

Figure 4.10: An example of two outliers that could be related to topography and slope.

4.2.3. Changes in Acoustic Measurements with Depth

The attenuation of light with increasing depth is one of the major factors determining kelp growth and the relationship between depth and bio height and hence signal strength and PVI. The example, Figure 4.11, shows the steady decline in PVI with increasing depth from 2m whilst both bio height and signal strength increase between 2 and 4m and reach a plateau before declining slowly until about 13m whereupon they decline sharply as depth increases further. The acoustic trends for PVI and bio height mirror the biological variables kelp biomass and kelp height respectively, as established through the kelp sampling program.

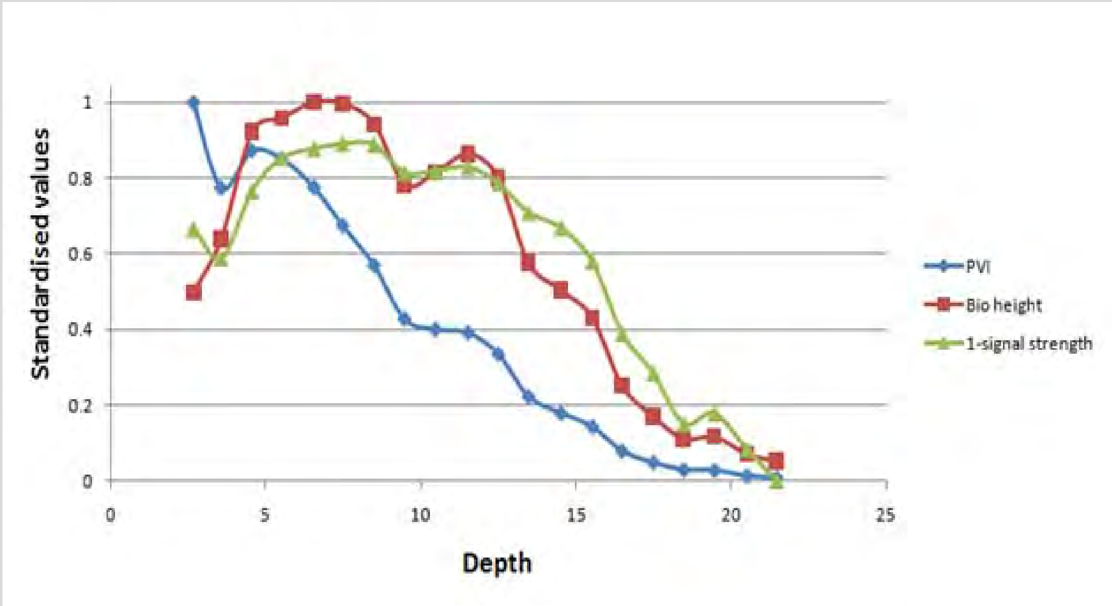

Figure 4.11: The relationship between depth and percent volume inhabited (PVI), bio height and signal strength (1 - decibel value). PVI declines gradually with depth whilst bio height and signal strength rise to a plateau and then decline at about 12 m.

4.2.4. Video Detection of the Kelp Canopy and Substrate

The video camera and associated depth gauge can be useful as a guide to establish the distribution of kelp height. Measurements of kelp height plotted against depth reinforce other results showing that the maximum kelp height occurred between the depths of 5m and about 12m (Figure 4.12).

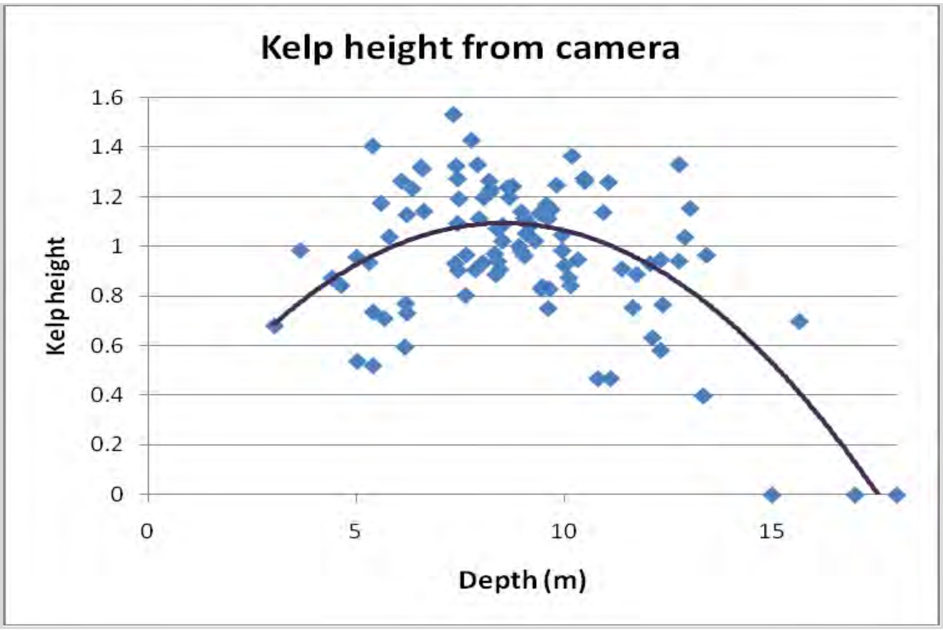

Figure 4.12: Scattergram of kelp height estimated from camera and depth gauge readings plotted against depth. Kelp height rises to a maximum between 5 and 12m and then declines with little kelp being found below 16m.

However, kelp height was difficult to measure accurately with the video camera because of the limited field of view through the camera (as compared to much better ability of divers to measure canopy height) and the video estimates of height correlated poorly with acoustically measured bio height.

4.3. Models Relating Acoustic and Biological Properties

4.3.1. Correlations between Acoustic Properties and Biomass

The data from both the sheltered and exposed sites from the south-west surveys were combined to create a dataset sufficiently large to calculate the regression of biomass against acoustic PVI and bio height. Since the diver observations included a limited number of locations with no kelp, additional records were added from the camera observations linking measurements of PVI and acoustic bio height with observations where biomass and kelp height were both nil. These records were added since, although it might be assumed that the regressions should pass through zero (no kelp = no PVI or acoustic bio height), some positive acoustic values might be found. The regressions of biomass against acoustic PVI and bio height for the summer 2009 survey (exposed and sheltered sites data combined as there was no significant difference between them) were both highly significant (Figures 4.13 and 4.14), although the spread of data about the regression line is quite wide (for example R^2 = 0.75 for PVI).

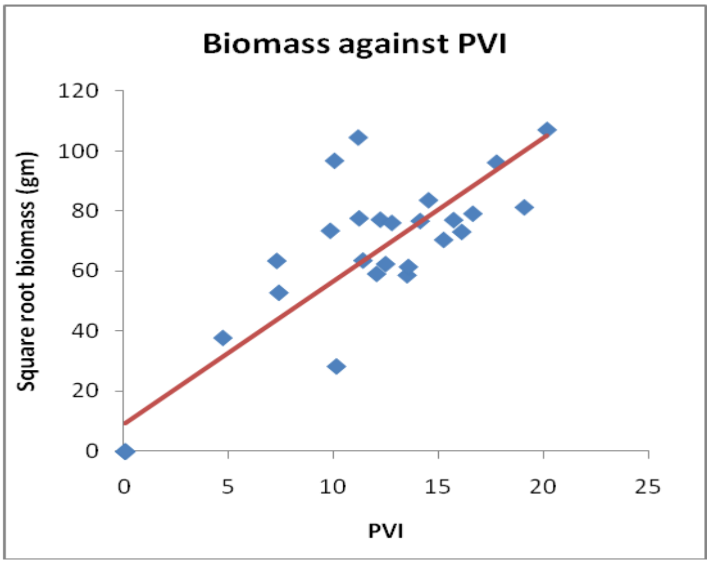

Figure 4.13: Regression plot and line fit for biomass against PVI using data from the south-west survey, summer 2009?: Square root biomass = 9 + (4.76 x PVI); R^2 = 0.76 (proportion of variation explained by PVI); Slope coefficient highly significant ($p<0.05$); Standard error (SE) of slope coefficient = 0.51.

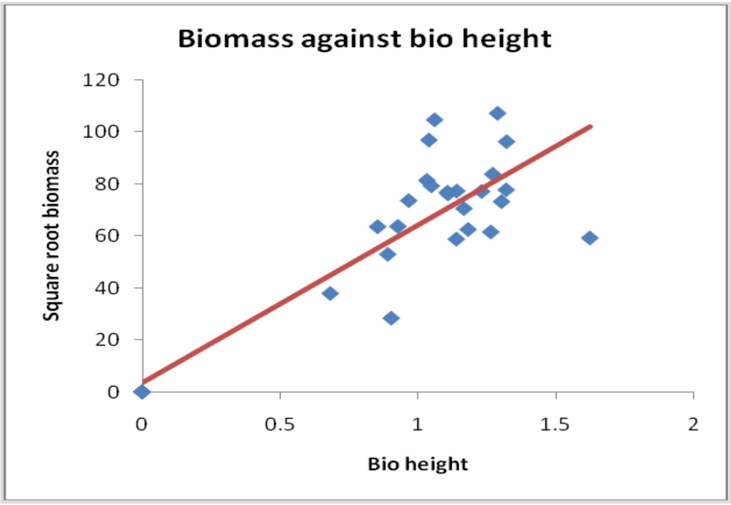

Figure 4.14: Regression plot and line fit for biomass against bio height using data from the south-west survey, summer 2009: Square root biomass = 3.9 + (60.4 x bio height); R^2 = 0.75 (proportion of variation explained by bio height); Slope coefficient highly significant ($p<0.05$); Standard error (SE) of slope coefficient = 6.7.

The regressions above represent those from the summer 2009 survey and it was considered possible that the relationship between the acoustic measurements and biomass might vary between seasons. The relationship obtained for the summer data was thus compared to that for the spring 2009 survey, even though the expected biomass values for spring and summer might not represent the maximum and minimum for the whole yearly cycle. However, the differences between the regression equations for the spring and summer surveys were not significant and there was no obvious seasonal difference in the relationship between the acoustic measurements and biomass.

4.3.2. Applying the Regression Model to New Data

It was necessary to establish whether the regression equations obtained from the south-west sites could be applied to acoustic data from other locations to predict biomass. The predictive power was tested by applying the regression equations from the data obtained during the summer south-west survey to the acoustic dataset collected at the west coast sites.

A paired 't-test' was performed to establish if there was any significant difference between predicted and actual biomass using the PVI regression equation. The mean difference (-13.3) was significantly less than zero (t [23 df] = 3.01; p = 0.006). The 95% Confidence Interval (CI) about the mean difference was -4.32 and -23.3. This suggests that the regression equation under-predicted the biomass for the west coast. However, given the SE of the slope coefficient (as reported in the previous section) of the regression equation, it is likely that the level of under-prediction was marginal.

One way to demonstrate predictive power of the regression equation in assessing biomass is to state what proportions of the predictions are within an acceptable margin of error from the observed. On this basis, it might be expected that a few predictions could be wide of the mark but that this be accepted as long as the majority of the predictions are reasonably accurate. However, predictive power cannot be calculated for the same dataset from which the equations were derived: the equations must be applied to new acoustic data. The equations derived from the south-west surveys were, therefore, applied to the west coast acoustic datasets.

The equations were applied to PVI and bio height and the deviations of the predicted values from those observed were calculated. The observed samples were then ordered by increasing deviation from the predicted and plotted against deviation (expressed as predicted/observed x 100) – see Figure 4.15. PVI was more successful as a predictor of biomass than bio height. About 80% of the biomass values predicted from PVI measurements were within 16% of the actual biomass and 50% of the observations were within 10% of the observed biomass.

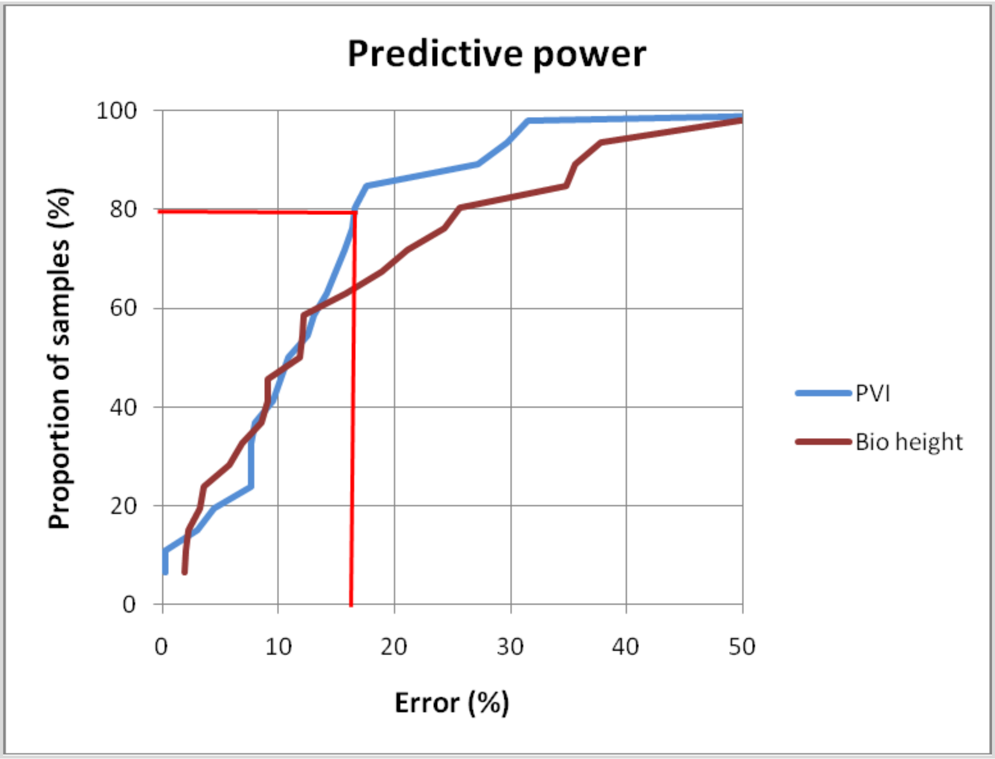

Figure 4.15: The regression equations of biomass against PVI derived from the south-west survey predicted the biomass at the west coast survey with an error of 16% or less in 80% of the sites surveyed on the west coast.

4.3.3. Spatial Interpolation of Acoustic Data and Distribution of Biomass

The process of interpolating acoustically measured PVI data to create contour maps of the distribution of kelp in each of the survey areas is shown in Figure 4.16. The distribution of the kelp is generally consistent with the diver established depth profile found in these areas, with taller more dense kelp beds found in shallower waters (Figures 4.17-20). The maps also show that the kelp biomass distribution has a sharply defined transition zone between dense kelp with high biomass and very sparse or no kelp (Figures 4.17-20).

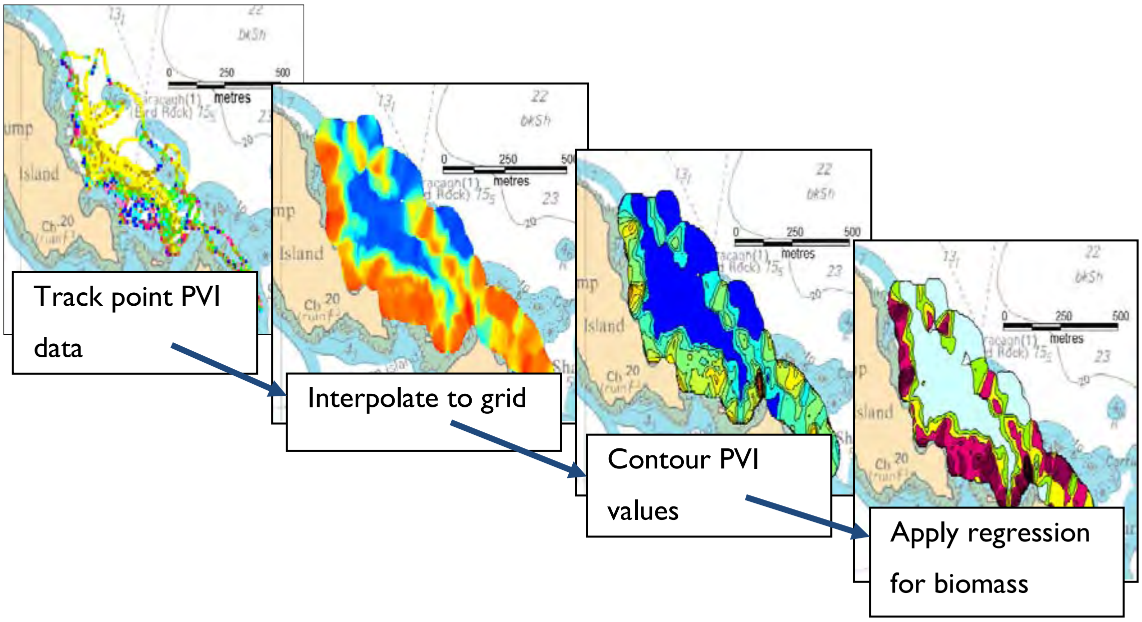

Figure 4.16: Stages in converting PVI records to map the distribution of kelp biomass for the Crump site in the west coast survey. © Crown Copyright and/or database rights. Reproduced by permission of the Controller of Her Majesty's Stationery Office and the UK Hydrographic Office (www.ukho.gov.uk). Not to be used for navigation.

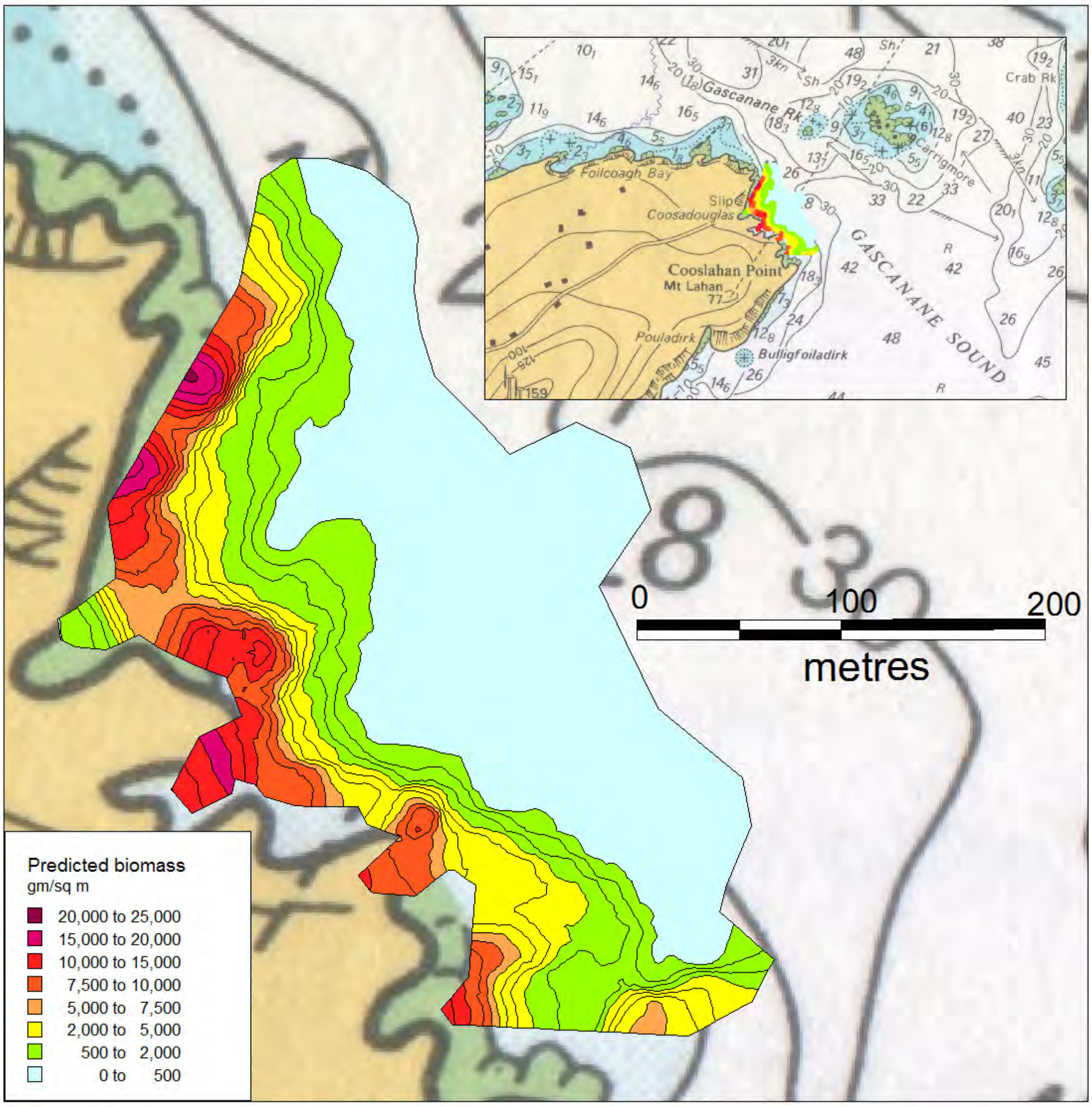

Figure 4.17: Map of predicted biomass (g/m²) for Slip site, south-west survey. © Crown Copyright and/or database rights. Reproduced by permission of the Controller of Her Majesty's Stationery Office and the UK Hydrographic Office (www.ukho.gov.uk). Not to be used for navigation.

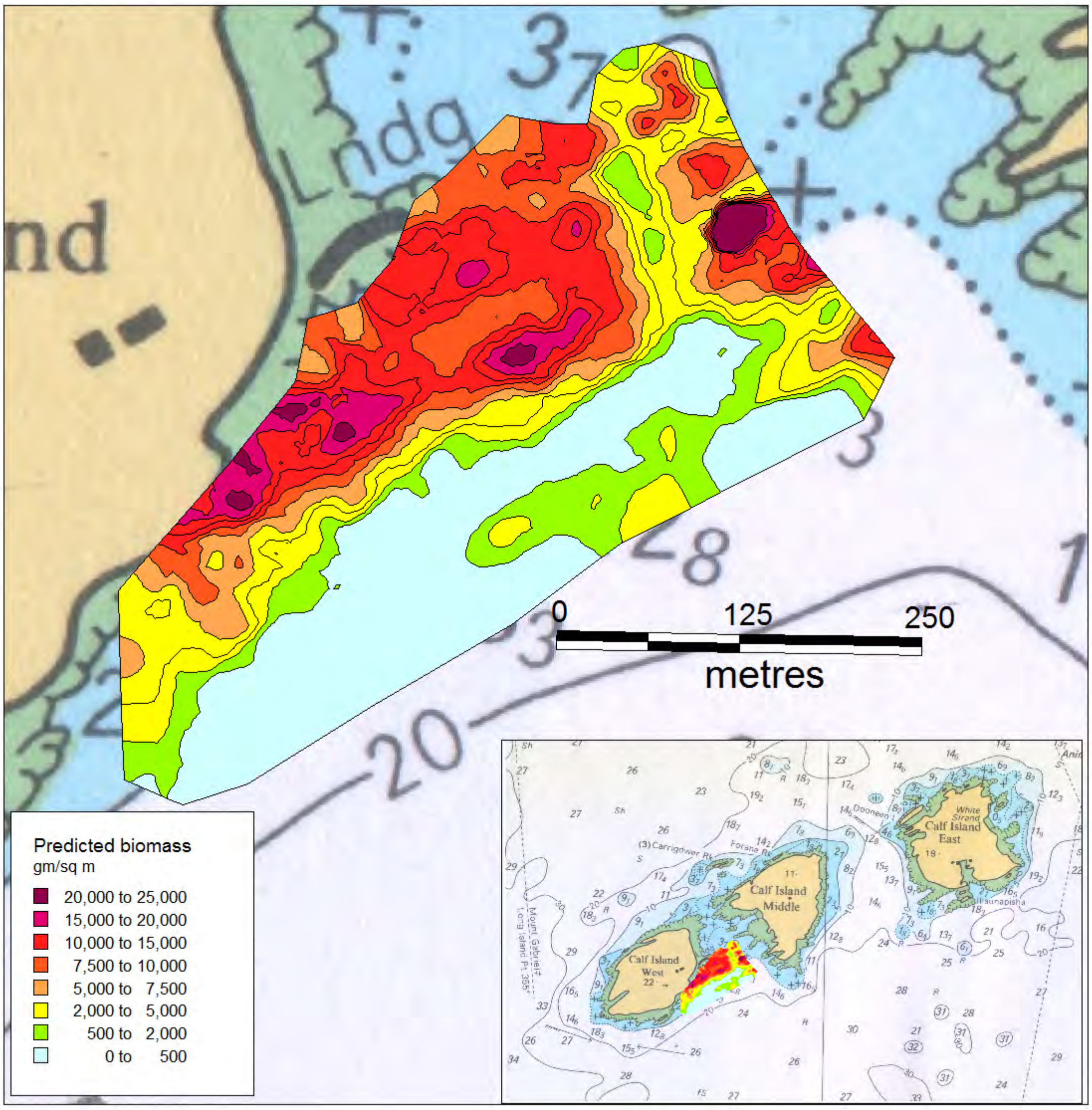

Figure 4.18: Map of predicted biomass (g/m²) for Calf site, south-west survey. © Crown Copyright and/or database rights. Reproduced by permission of the Controller of Her Majesty's Stationery Office and the UK Hydrographic Office (www.ukho.gov.uk). Not to be used for navigation.

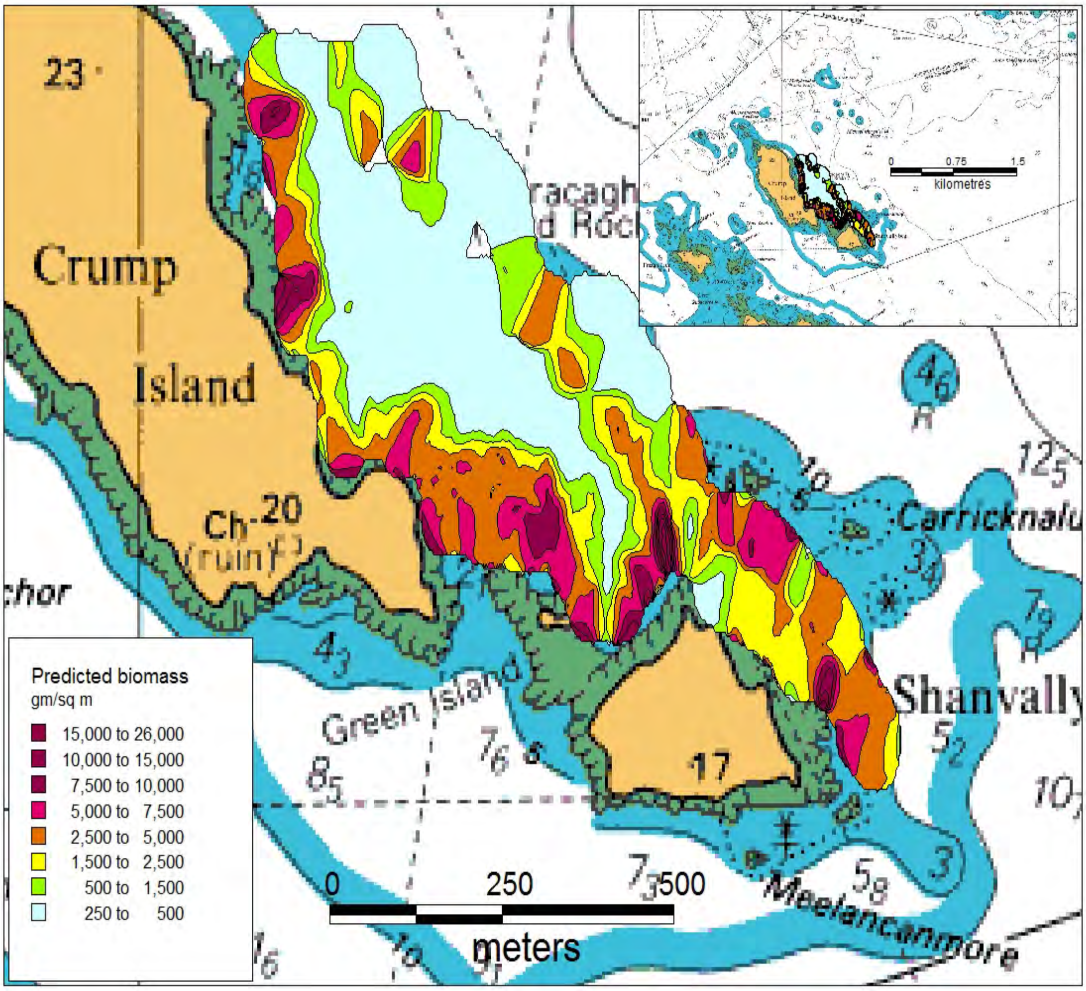

Figure 4.19: Map of predicted biomass (g/m²) for Crump site, west coast survey. © Crown Copyright and/or database rights. Reproduced by permission of the Controller of Her Majesty's Stationery Office and the UK Hydrographic Office (www.ukho.gov.uk). Not to be used for navigation.

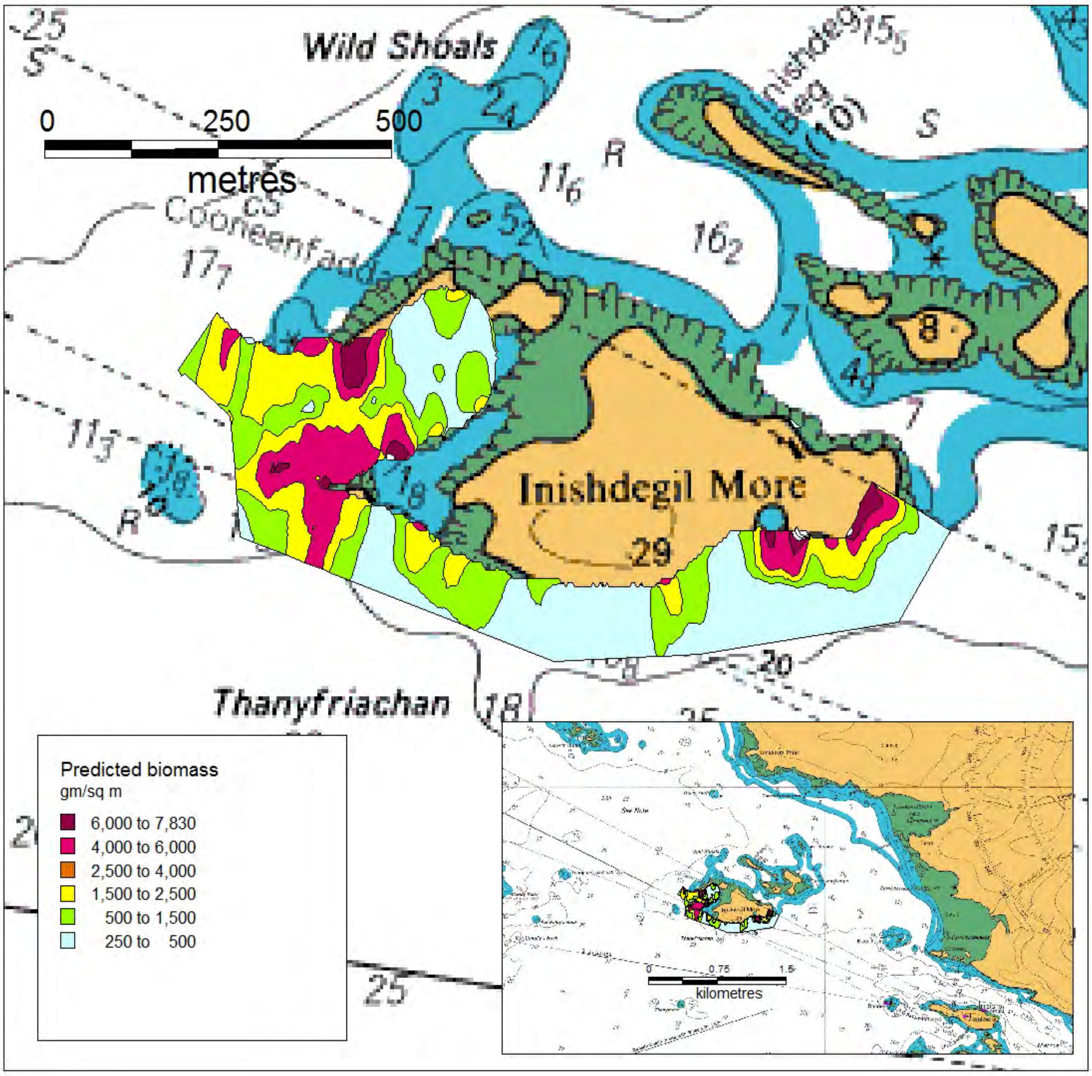

Figure 4.20: Map of predicted biomass (g/m²) for Inishdegil site, west coast survey.

The biomass within an area is concentrated in areas of high density (biomass/m²). This is clearly illustrated in Figure 4.21 from the south-west survey, despite the majority of the survey area having low PVI values, the majority of the total biomass is from areas where the PVI values were between 13 and 21. However, the overall assessment of biomass from a given area is subject to uncertainty. The biomass maps can be used to calculate a total biomass expected for the area surveyed. Also, the upper and lower 95% confidence interval of the regression slope can be used to derive the maximum and minimum total biomass that might be expected. Table 4.1 is a summary of the estimated biomass for four survey sites: two from the south-west survey and two from the west coast survey. Data in Table 4.1illustrate the biomass that might be available for harvesting in these areas.

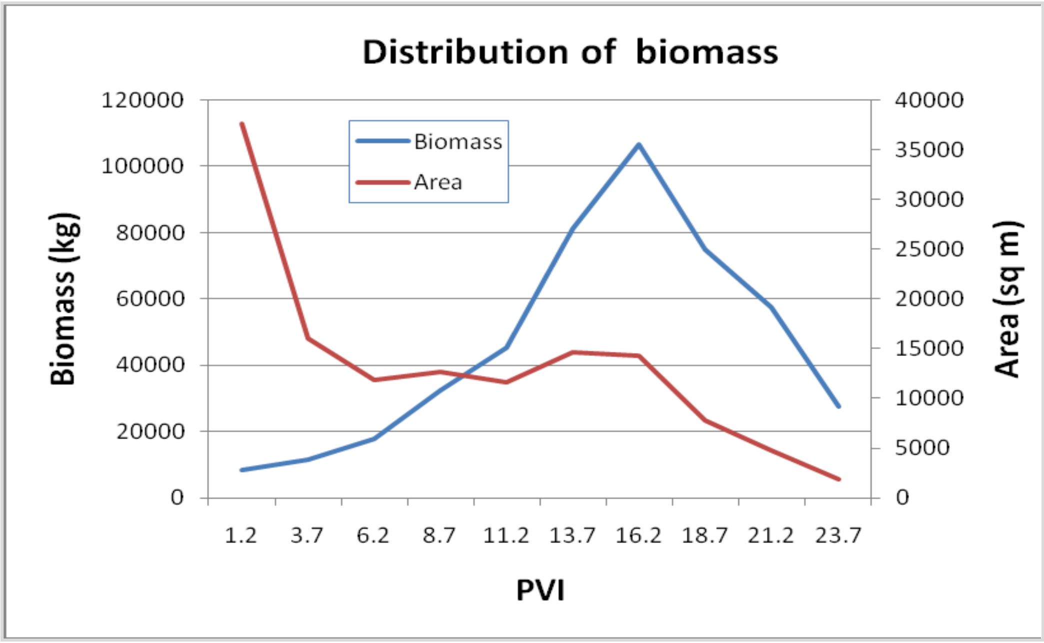

Figure 4.21: Distribution of biomass relative to acoustic PVI.

Table 4.1: Summary of total kelp biomass predicted from acoustic data for the 4 survey areas.

Sites (SW – south-west; W – west coast)	Area surveyed (hectares)	Biomass (kg x 1000)		
		Predicted (mean)	Upper 95%	Lower 95%
Calf site (SW)	13.3	463.2	658.35	302.5
Slip site (SW)	7.6	275.1	393.6	117.9
Inishdegil site (W)	19.9	330.8	459.1	224.3
Crump site (W)	35.2	905.6	1276.4	598.9

4.4. Species Transition Zone

Examination of the data referring to the species transition from *L.. hyperborea* in deeper water to *L.. digitata* in the shallow subtidal in the south-west surveys showed a consistent relationship within each site but not between sites. The sheltered site on the south-west surveys, the Slip, showed that the main change in dominance of the two species of kelp occurred at around chart datum, approximately 0.6 m below the mean low water of spring tides (MLWS) (Figure 4.22). However, at the exposed site, the Calf, the change occurred at around 1m below chart datum, which is approximately 1.6m below MLWS (Figure 4.22). There was considerable overlap in the distribution of the two kelp species at both sites, with *L.. digitata* and *L.. hyperborea* coexisting for a depth range of 2-3m (Figure 4.22). It was observed that, at depths where *L.. digitata* was usually absent from the substrate due to light limitation, it was often found growing epiphytically on the stipes of *L.. hyperborea* specimens where the light environment was more favourable. Once the *L.. hyperborea* canopy was below this light limit, *L.. digitata* were no longer found growing on the stipes of their congenerics. The two sites in the west coast survey showed no difference in the depth of the transition of the two species. The transition zone at both west coast sites is at a similar level to that observed at the sheltered site in the south-west survey, with the main transition occurring at around chart datum which was approximately 0.8m below MLWS at the west coast site (Figure 4.23).

Examination of the acoustic data found no difference in the signal or the derived parameters between the zone dominated by *L.. digitata* and the zone dominated by *L.. hyperborea*. It was, therefore, not possible to differentiate between the two species based on the acoustic technique developed here.

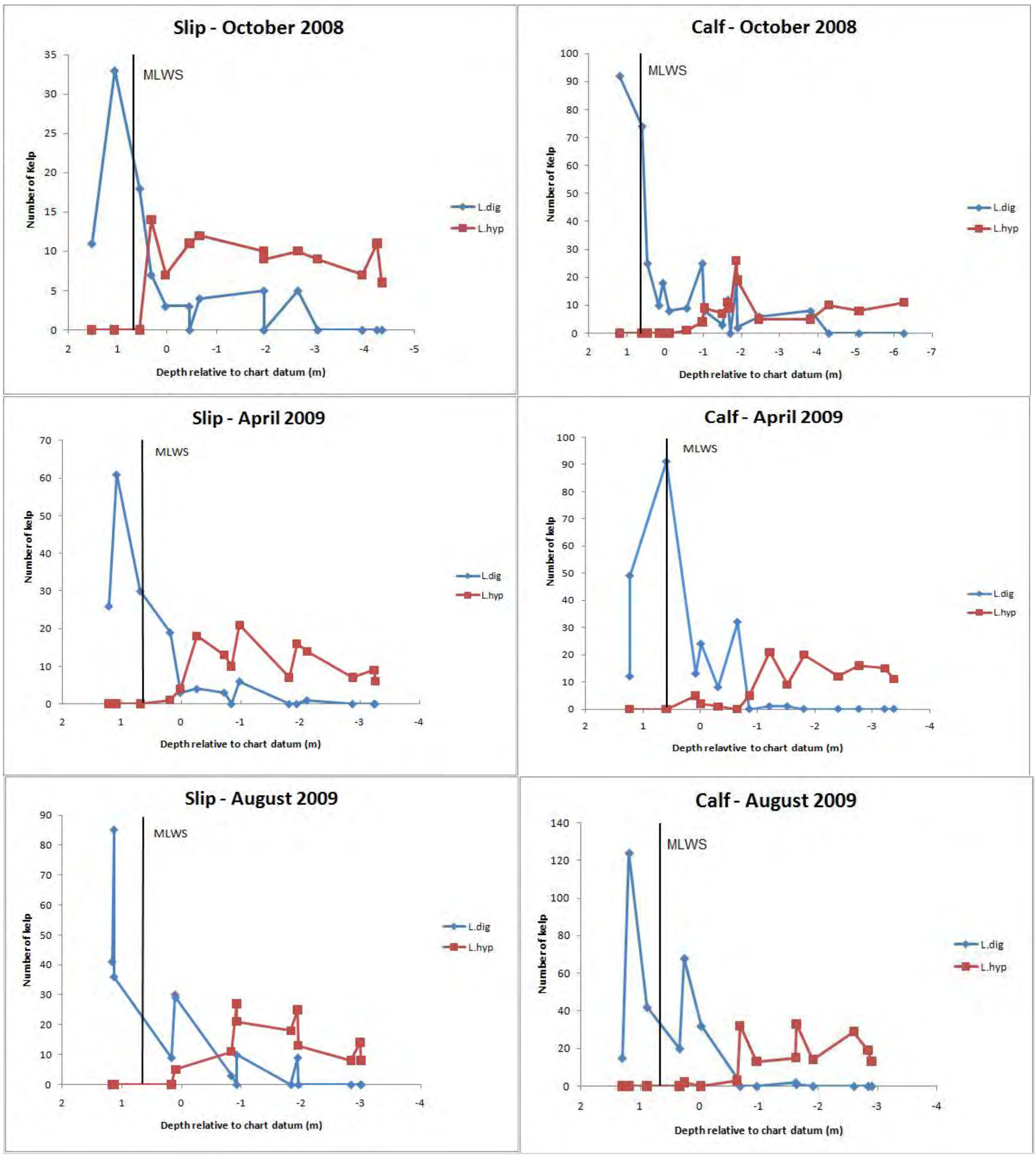

Figure 4.22: Depth and density (per 0.25m²) distribution of *L.. digitata* and *L.. hyperborea*, relative to chart datum, for the south-west surveys.

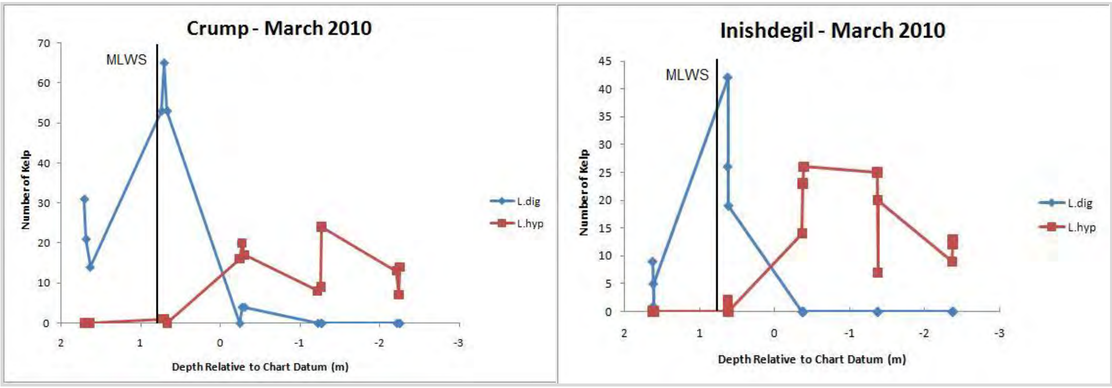

Figure 4.23: Depth and density (per 0.25m²) distribution of *L. digitata* and *L.. hyperborea*, relative to chart datum, for the west coast survey.

4.5. Growth of Laminaria hyperborea

Growth of *L.. hyperborea* was monitored at the two sites in the south-west survey (Slip & Calf) for the duration of the project. This enabled examination of changes in the structure and biomass of the kelp beds in the context of the seasonal growth patterns of the kelp. The seasonal pattern of growth in *L.. hyperborea* was consistent with data in the literature and with the main growth season occurring between late winter and late summer (Figure 4.24). The period of growth for the stipe appeared to be more prolonged than that for the lamina, in which growth appeared to have almost ceased by late spring (Figure 4.24). The growth of the stipe also appeared to be consistently greater at the Calf site (exposed) than at the Slip site (sheltered) (Figure 4.24). The lamina, however, showed little variation in its growth between the sheltered and exposed sites (Figure 4.24). The higher stipe growth at the Calf site appears to be driven largely by the intermediate-sized specimens (stipe length 30-80cm), although growth in all size categories was greater than that at the sheltered site.

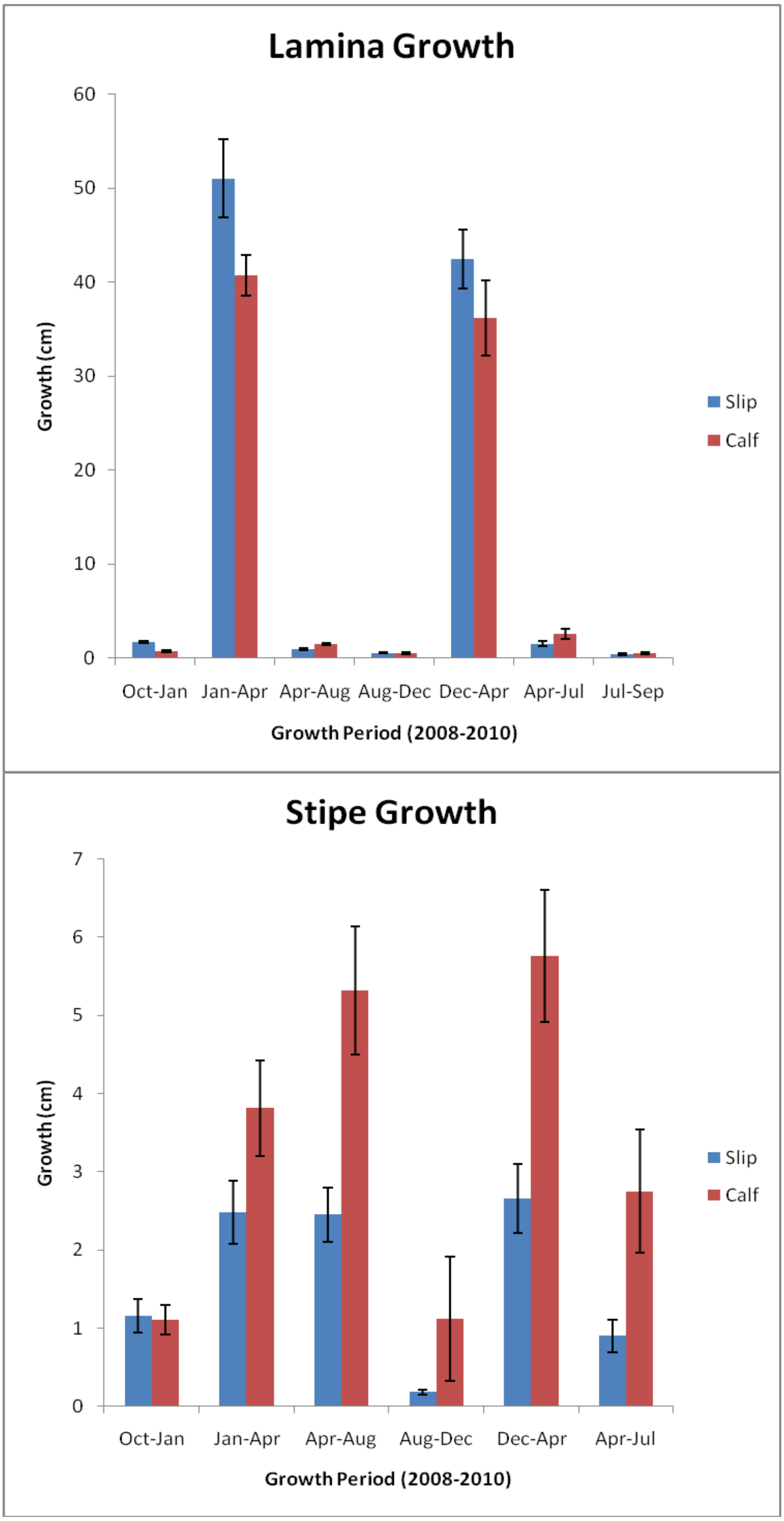

Figure 4.24. Total growth of the lamina (top) and stipe (bottom) for *L.. hyperborea* (with standard error) at the south-west survey sites.

5. Discussion

5.1. Biological Sampling

5.1.1. Site Characteristics

Although the kelp biomass at the south-west survey sites varied with season, it showed no significant difference between the levels of exposure within each season. However, the level of exposure appeared to influence the density within the kelp beds. The exposed site in the earlier south-west surveys had a higher plant density which was driven by the number of juvenile plants. This however, was insufficient to affect the biomass but purely reflected the differences in the population size structure between the two sites. The exposed site not only had a high number of juveniles but also showed a greater variation in the size range of the plants and consistently had the largest specimens. This was not only apparent in the sample data but was also confirmed through diver observation which indicated that the Slip site (sheltered) had a very uniform population of even size classes, whereas the Calf site (exposed) had a very uneven size structure. Disturbance events, such as storms, are a regular feature affecting the structure and dynamics of kelp beds and therefore the Calf site would be expected to be subject to relatively more of these events. This would lead to loss of weaker or older specimens resulting in breaks in the canopy. The reduction in canopy cover and biomass supports a higher recruitment and growth of the understorey plants (Sjøtun et al., 1998), which is likely to have given rise to the higher number of juveniles observed at the Calf site. The same pattern of similar biomass but different densities was also observed at the two west coast sites, although these sites overall had higher plant biomass and density.

During the diving surveys, kelp was observed in closed canopies down to a depth of 12-13 m and was usually absent below 17-19m. The depth distributions and the light profiles as measured during each survey are consistent with established lower light limits of the kelp *L.. hyperborea* (Lüning, 1990). However, the depth limitations will vary locally according to specific environmental conditions particularly the turbity of the water.

Site selection has important implications for the success of any potential kelp harvesting industry. It was observed in the surveys that in more offshore locations, i.e. clearer shallow water and islands beyond the influence of fresh water run-off, kelp is distributed to greater depths. This will make offshore islands of significant socioeconomic interest to any harvesting industry. In order for an industry to be sustainable, the succession and rate of recovery of a harvested area needs to be considered and the differences between sites identified in the present surveys may prove to be of significance in the choice of location.

5.1.2. Morphology and Biomass

The strongly significant relationship between the stipe length of individual specimens of *L. hyperborea* and their total biomass has the potential to be an important tool in the estimation of kelp bed biomass. The lamina of kelp are slightly negatively buoyant and therefore tend to hang down in the water column or spread laterally under the influence of wave induced currents. Therefore, acoustic detection of the upper boundary of the kelp canopy, together with the assumption that the laterally spread canopy will have only a limited vertical distribution, will allow an estimate of the height of the kelp, i.e. their stipe length. This information can then be used, in conjunction with an assessment of kelp density, to provide a quantitative estimate of the total biomass in a kelp bed. This approach will be incorporated in the analysis of the acoustic data later in this report and used to relate the acoustic response to kelp biomass.

5.1.3. Species Transition Zone

The transition from the dominance of *L. hyperborea* in deeper water to that of *L.. digitata* in the shallow subtidal has been shown to be site specific and dependent on local environmental conditions. Although the depth relative to chart datum of the transition between the species was consistent between replicate transects within a survey site, the height of the transition zone relative to chart datum varied between sites at the same locality (south-west survey) reflecting the degree of exposure and also between localities for similar subjectively assessed degrees of exposure. The overlap in the distribution of the two species of kelp meant that *L.. digitata* extended down to 2 or 3m below chart datum, albeit at lower densities, which was well inside the *L.. hyperborea* zone. Therefore, no clear separation of the two species can be made for the purposes of resource assessment. Assessment of the potential value of an area for the harvesting of kelp, particularly *L.. digitata*, would require accurate definition of the depth of the transition zone which, clearly, will require information on the degree of exposure of the site. However, more work covering a wider range of conditions is necessary to establish a solid relationship.

5.1.4. Growth of Laminaria hyperborea

Growth rates of *L. hyperborea* at the south-west survey sites were consistent with that presented in the literature, with the main growth season occurring between late winter and late summer (Kain, 1979). Lower growth rates were seen in kelp beds with an established canopy, which suppresses growth of understorey plants (Sjøtun et al., 1998). Such conditions were evident at the slip site (sheltered) which was characterised by a very even and largely unbroken kelp canopy. Growth rates of older canopy plants were not significantly influenced by canopy biomass and showed steady seasonal growth patterns; however, they did show increased growth rates in exposed areas as shown by Sjøtun et al. (1998). The Calf site (exposed) showed higher growth rates, particularly in the stipe. The higher allocation of annual growth to the stipe at the exposed site, particularly in the intermediate-sized specimens, is consistent with Sjøtun et al. (1998) who reported rapid stipe elongation in this size category at wave-exposed sites. The rapid stipe growth is seen as a response by kelp about to grow into the canopy-forming layer (Sjøtun et al., 1998).

5.2. Acoustic Surveys

The ability of the higher frequency (200 kHz) to detect the seafloor and macrophytic zone with less backscatter in the water column has important implications for the autodetection of the kelp because of the reduced amount of operator input needed to 'clean up' the data. However, even the cleaner signal will have a certain amount of variability which is associated with uneven topography and the natural variation within a kelp bed. Using mean values for the acoustically detected kelp zone helps lessen this variability by reducing the effect of outliers (occasional measurements that depart greatly from the general trend). The smoothing and aggregation of the data in the generation of kelp resource maps, as described later in the report, has a similar effect and allows production of estimates of kelp cover at a scale which is pertinent to harvesting practices and resource assessment.

The acoustically determined depth profile of the kelp beds shows a highly significant relationship with the detailed plant data from the diver sampling and observations. All acoustic surveys were conducted on spring high tides to ensure maximal coverage of the kelp beds into the intertidal zone. The sharp increase in detected bio-height of the kelp plants and signal return between 2m (intertidal) and 4m (subtidal) depth is therefore consistent with the progression from intertidal communities to the higher biomass kelp communities in the shallow subtidal. There was a slow decrease in all acoustic parameters down to a depth of 13m, after which they declined sharply with any increase in depth. This is consistent with the depth distribution of the 'closed canopy' kelp beds which occur down to 12-13m and thin rapidly below this depth. This observation was also confirmed through the use of the drop down camera. The acoustic trends for PVI and bio height reflect the trends in kelp biomass and kelp height respectively; demonstrating that the technique developed here is highly effective at detecting the general characteristics of a kelp bed.

There was a strong relationship between diver sampled kelp biomass and the acoustically measured PVI and bio height, although there was a moderate level of uncertainty in the relationships. There are a number of sources of uncertainty in the prediction of biomass from the acoustic measurements, some of which have been discussed previously. These include measurement error (problems of positioning, the difficulty of collecting samples and the inherent variability of the echo) as well as the stochastic variation in kelp density and growth. Some outliers have also been recorded and many have been associated with steep slopes or rugged rock surfaces that are known to affect echo reflection properties. These outliers have, however, been included in the analysis. Despite this, the smoothing technique developed in the analysis minimises the effects of these sources of error and the relationship between acoustic parameters and sampled biomass appears consistent and can be used to predict kelp biomass.

There was no significant seasonal difference in the regression relationship for the acoustic parameters and kelp biomass between the two south-west surveys (spring and summer 2009). The diving surveys identified a significant difference in the mean kelp biomass between seasons. Therefore, despite seasonal changes in the mean biomass, the relationship between acoustic parameters and kelp biomass remained constant.

The variation in the biomass of dense kelp beds between that found at the south-west survey sites and that of the west coast survey sites, with the latter having the higher overall biomass, was reflected in the acoustic data. Importantly, the regression equation generated from data for the south-west surveys and applied to the acoustic data for the west coast survey, correctly predicted the higher biomass found on the west coast. This result is very reassuring and indicates that the acoustic survey approach may be used in situations outside of the conditions of the surveys.

The acoustic surveys demonstrated a clear transition from dense kelp beds to sparse or empty areas in both survey areas. This has important implications for the detection of dense stands of kelp and the estimation of biomass from the point of view of potential harvesting: dense kelp would appear to be well defined spatially and the transition zone can be confidently mapped. The error associated with biomass estimation might have been more significant for environmental management programmes (for example, deciding where to stop harvesting due to low expected biomass) if there had been an extensive transition zone of increasingly sparse kelp. Thus, the demarcation of areas likely to return high biomass, using acoustic survey techniques, would appear to be robust based on the evidence from these surveys.

The acoustic technique could not be used to distinguish between the two species of kelp. Analysis of the acoustic signal and derived parameters did not identify a difference between the monospecific stands of *L.. digitata* and *L.. hyperborea*. The lack of acoustic distinction is not surprising given the morphological similarity between the two species, particularly while submerged. This is further complicated by the overlap in their vertical distribution and the observation that *L.. digitata* grows epiphytically on *L.. hyperborea*.

5.3 Conclusions

The study shows that it is possible to use a readily available fisheries echosounder to give an estimation of kelp biomass that would be of relevance to the assessment of the stock of kelp biomass in an area. Sonar5Pro proved to be a suitable tool for the analysis of the echograms and the additional facility to measure percent volume inhabited (PVI), written for this program by Helge Balk, gave the most precise information about biomass. Bio height was almost as informative.

There was a wide margin of error about the predictions, but these were of lesser significance when the spatial distribution of biomass is considered: the areas of high biomass were well defined and sharply delineated from sparse kelp and this supports the use of acoustics to survey for areas that are likely to yield a high biomass.

The predictions of biomass were based on limited survey data and it is possible that the relationship between the acoustics and biomass might vary between areas. Thus, the application of a uniform regression equation may overestimate or underestimate biomass. The application of the regression equation derived from the south-west survey to the west coast survey suggested that there was an underestimation. The difference was not great and was unlikely to affect commercial decisions about harvesting. However, local calibration of the acoustic system may be advisable if the margin of error is considered important.

The more widespread use of the acoustic methodology to assess kelp stocks on a much larger scale, such as a regional or national assessment, may require more careful calibration around the coast to account for regional differences in kelp growth and the relationship with the acoustic parameters.

The study focussed on one system, the fisheries SBES, and no comparison was made with other sonar systems. The choice of the system was carefully matched to the likely requirements of users from industry, rather than purely for research. The system has the advantages of portability, user-friendly software, relatively fast data analysis, relatively low-cost operational expenses and ease of integration with GIS applications. The system has the potential for highly cost effective detection and mapping of kelp. Its greatest utility would be for mapping medium-scale areas (in the order of $1km^2$), particularly with poor water clarity (Sabol et al., 1996). Schneider et al., (2001) note that single beam fisheries sounders proved relatively easy to use. They conclude that the main advantage is the rapid and complete assessment of an entire area and the quick availability of data.

5.4. Application of Technique

The principal aim of the project was to develop and demonstrate an acoustic methodology for the estimation of kelp biomass. The project has successfully developed the methodology based on a readily available commercial acoustic system and modification of the standard software. During the course of the project, discussion has been carried out with representatives of a number of organisations potentially interested in the commercial exploitation of kelp. Over the grant period it is clear that there have been major developments of interest in the potential commercial use of kelp. Large-scale harvesting of kelp has, (to the best of our knowledge), not commenced in Ireland, nevertheless the expressions of interest have led to a number of research grants investigating the potential for large-scale kelp use such as in the pharmaceutical industry and for biofuels. Ireland has a particularly strong base in applied and ecophysiological macroalgal research and is well placed to exploit the future potential of this resource. The present project provides a valuable addition to this base by allowing a rapid assessment of kelp biomass on a commercially relevant spatial scale.

The various possible commercial uses of kelp include:

1. <u>Energy Source - Anaerobic Digester (AD) conversion</u>. This is currently a very active field of interest: it won't use up agricultural land; for the supply of an energy resource; the 'soft' carbon content of macroalgae in relation to digestion requirements; and the rapid growth of kelp. Three substantive on-going or recently completed grants are actively contributing to background information. An ITI Scotland grant (QUB, B9 Organic Energy NI) demonstrated from detailed laboratory studies the feasibility of using *L.. hyperborea* as an energy source for AD. The BIOMARA project, fronted by SAMS, is a major EU-funded project investigating a comprehensive range of topics related to the commercial use of kelps as an energy source for AD. BIOMARA has an extensive range of partners from the EU with interests extending from kelp biology

and ecology, biomass availability through to the economics and social benefits of kelp exploitation for energy generating purposes. A further EU-funded project, MABFUEL, is also actively investigating aspects of macroalgal ecology and suitability related to its use as an energy source, including via AD. It is recognised that basic AD technology is now well established and QUB have been in discussion with B9 Organic Energy and other commercial organisations to investigate the feasibility of setting up a test AD facility using kelp as the base energy supply.

2. Energy Source (Supercritical Oxidation). Although supercritical oxidation is not as well developed as an energy sourcing process as AD, nevertheless it has several potential advantages, particularly related to the high efficiency of the process. A recent Intertrade Ireland grant, which made specific reference to the use of macroalgae as an energy source for supercritical oxidation, is assessing the potential for supercritical oxidation as a valuable adjunct to the generation of electricity.

3. High-Value Products. The majority of high-value products derived from kelp relate to pharmaceuticals, particularly as derived from *L.. digitata*. It is understood that limited harvesting is carried out in the west of Ireland for this purpose. Considerable effort is being put into the identification of high-value products and it is expected that pressure on harvesting for these purposes will increase.

4. Fertiliser/Plant Growth Promoting Substance Extracts. A commercial organisation in the Orkney Islands harvests kelp for the extraction of a combined fertiliser product/plant growth-promoting substances. There is the possibility of extending this type of operation to Ireland.

5. Shellfish Food. Small quantities of kelp are currently harvested for use as food for *Abalone* aquaculture. This requirement will increase with any expansion of aquaculture initiatives for the high-value *Abalone*.

6. Management Plans. The approach will also be of significant value to regulatory authorities for the monitoring of healthy kelp beds and their associated fauna and flora, and will aid in the evaluation of the recovery in harvested areas.

For any commercial demand for kelp, in addition to employing the developed technique to assess stocks, it will also be essential to monitor the harvesting and recovery rates of the kelp beds to ensure a sustainable resource. The acoustic technique will provide a particularly valuable tool for regulatory authorities to check the location of harvested areas and also to monitor kelp recovery rates post-harvesting. A major advantage of the acoustic approach for estimating kelp biomass is compatibility of the spatial scale of the acoustic sampling with the typical spatial scale of harvesting areas.

References

Anderson, R.J., Rand, A., Rothman, M.D., Share, A. and Bolton, J.J. (2007). *Mapping and quantifying the South African kelp resource*. African Journal of Marine Science 29:369-378.

Balk H. and Lindem T. (2005). *Sonar4, Sonar5 and Sonar6 post processing systems*. Operator manual version 5.9.6 380p., Lindem Data Acquisition Humleveien 4b. 0870 Oslo Norway.

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

Birkett, D.A., Maggs, C.A., Dring, M.J. and Boaden, P.J.S. (1998). *Infralittoral reef biotopes with kelp species (Volume VII). An overview of dynamic and sensitivity characteristics for conservation management of marine SACs*. Scottish Association of Marine Science (UK Marine SACs Project).

Bixler, H.J. and Porse, H. (2010). *A decade of change in the seaweed hydrocolloids industry*. Journal of Applied Phycology DOI 10.1007/s10811-010-9529-3.

Blondel, Ph. and Murton, B.J. (1997). *Handbook of Seafloor Sonar Imagery*. PRAXIS-Wiley and Sons 314 pp.

Bruno, J.F. and Bertness, M.D. (2001). *Habitat Modification and Facilitation in Benthic Marine Communities*. In Bertness, M.D., Gaines, S.D. and Hay, M.E. 2001. Marine Community Ecology. Sinauer Associates, Inc., Massachusetts.

Chivers R.C., Emerson N. and Burns D.R. (1990). *New acoustic processing for underway surveying*. The Hydrographic Journal 56:8-17.

Collins, K. (2009). *Comparison of video sledge and echo-sounder results for seagrass surveys in Studland Bay and Poole Harbour*. Draft Report to Natural England.

Collins, W.T., Preston, J.M., Christney, A.C., and Rathwell, G.J. (2002). *Production Processing of Multibeam Backscatter Data for Sediment Characterization*. Quester Tangent Corporation, 99-9865 West Saanich Road, Sidney, BC, Canada

Cutter, G.R., Rzhanov, Y. and Mayer, L.A. (2002). *Automated segmentation of seafloor bathymetry from multibeam echosounder data using local Fourier histogram texture features*. Journal of Experimental Marine Biology and Ecology 285-286: 355-370.

Dayton, P.K. (1985). *Ecology of kelp communities*. Annual Review of Ecology & Systematics 16: 215-245.

Davidson, S. (2006). *Sounding out the seabed*. ECOS 129:34.

Deysher, L.E. (1993). *Evaluation of remote sensing techniques for monitoring giant kelp populations*. Hydrobiologia 260/261:307-312.

Duggins, D.O., Simenstad, C.A. and Estes, J.A. (1989). *Magnification of secondary production by kelp detritus in coastal marine ecosystems*. Science 245:170-173.

Eckman, J.E., Duggins, D.O. and Sewell, A.T. (1989). *Ecology of understory kelp environments. I. Effects of kelps on flow and particle transport near bottom*. Journal of Experimental Marine Biology and Ecology 129:173-187.

Fortin, G.R., Saint-Cyr, L., and Leclerc, M. (1993). *Distribution of submerged macrophytes by echo-sounder tracings in Lake Saint-Pierre, Quebec*. Journal of Aquatic Plant Management 31:232-240.

Gagnon, P., Scheibling, R.E., Jones, W. and Tully, D. (2008). *The role of digital bathymetry in mapping shallow marine vegetation from hyperspectral image data*. International Journal of Remote Sensing 29:879-904.

Gerlotto, F., Soria, M. and Fre´on, P. (1999). *From two dimensions to three: the use of multibeam sonar for a new approach in fisheries acoustics*. Canadian Journal of Fisheries and Aquatic Sciences 56 (1):6 –12.

Guillaumont, B., Callens, L. and Dion, P. (1993). *Spatial distribution and quantification of Fucus species and Ascophyllum nodosum beds in intertidal zones using spot imagery*. Hydrobiologia 260/261:297-305.

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

Hass, C. and Bartsch, I. Accessed (2010). *Acoustic kelp bed mapping in shallow rocky coasts – case study Helgoland (North Sea): Implementation & Results*. Available at: http://epic.awi.de/Publications/Has2008f.pdf

Hennequart, F., Dalias, N., Barraqué Garat, P., Philip de Laborie, L. and Scourzic, T. (2006). *Review of kelp biomass assessment techniques – application to the inshore and coastal waters of Ireland*. OCEANIDE 167pp.

Hession, C., Guiry, M.D., McGarvey, S. and Joyce, D. (1998). *Mapping and assessment of the seaweed resources (Ascophyllum nodosum, Laminaria spp.) off the west coast of Ireland*. Marine Resource Series No. 5. Marine Institute, 74pp.

Hoffman, J. C, Burczynski, J, Sabol, B and Heilman, M. (2002). *Digital acoustic system for ecosystem monitoring and mapping: assessment of fish, plankton, submersed aquatic vegetation, and bottom substrata classification*. White Paper. BioSonics, Inc., 4027 Leary Way NW, Seattle, WA 98107, USA. Available at: http://www.biosonicsinc.com/doc_library/docs/lake_wa_assessment.pdf.

Jackson, E. (2003). *Importance of seagrass beds as a habitat for fishery species around Jersey*. Unpublished PhD thesis. University of Plymouth.

Kain, J.M. (1979). *A view of the genus Laminaria*. Annual Review of Oceanography and Marine Biology 17:101-161.

Kelly, E. (2005). *The role of kelp in the marine environment*. Irish Wildlife Manuals, No. 17. National Parks and Wildlife Service, Department of Environment, Heritage and Local Government, Dublin, Ireland.

Komatsu, T., Mikami, A., Sultana, S., Ishida, K., Hiraishi, T. and Tatsukawa, K. (2003). *Hydro-acoustic methods as a practical tool for cartography of seagrass beds*. Otsuchi Marine Science 28:72-79.

Kruss, A., Blondel, P., Tegowski, J., Wiktor, J. and Tatarek, A. (2008). *Estimation of macrophytes using single-beam and multibeam echosounding for environmental monitoring of arctic fjords (Kongsfjord, West Svalbard Island)*. Acoustics '08. Paris 2008

Kruss, A., Tegowski, J., Wiktor, J., Tatarek, A., Olenin, S., DaunyS, D., Gorska, N. and Klusek, Z. (2002). *Acoustic characterisation of benthic habitats in Hornsund Fjord (the Svalbard Archipelago)*. Proceedings of the Eighth European Conference on Underwater Acoustics, 8th ECUA. Edited by S. M. Jesus and O. C. Rodríguez Carvoeiro, Portugal 12-15 June, 2006.

Lüning, K. (1979). *Growth strategies of three Laminaria species (Phaeophyceae) inhabiting different depth zones in the sublittoral region of Helgoland (North Sea)*. Marine Ecology Progress Series 1:195-207.

Lüning, K. (1990). *Seaweeds: their environment, biogeography and ecophysiology*. John Wiley and Sons, Inc. New York.

Lurton, X. (2002). *An Introduction to Underwater Acoustics: Principals and Applications*. Praxis Publishing Ltd., Chichester, UK, 347 pp.

McCarthy, E.M. and Sabol, B. (2000). *Acoustic characterization of submerged aquatic vegetation: military and environmental monitoring applications*. IEEE 0-7803-6551-8.

National Seaweed Forum (2000). *National Seaweed Forum Report*. Dublin, Ireland.

Noel, C., Viala, C., Coquet, M., Zerr, B. and Perrot, T. (2008). *Acoustic data fusion devoted to underwater vegetation mapping*. Acoustics 08, Paris 6643 – 6646

North, W.J., James, D.E. and Jones, L.G. (1993). *History of kelp beds (Macrocystis) in Orange and San Diego Counties, California*. Hydrobiologia, 260/261:277-283.

Orlowski. A.O. (1984). *Application of multiple echoes energy measurement for evaluation of seabottom type*. Oceanologica 19:61-78.

Parke, M. (1948). *Studies on British Laminariaceae. I. Growth in Laminaria saccharina (L.) Lamour*. Journal of the Marine Biological Association of the UK 27:651-709.

Preston, J, Inouchi, Y. and Shioya, F. (2006). *Acoustic classification of submerged aquatic vegetation*. Proceedings of the Eighth European Conference on Underwater Acoustics. ECUA 2006

Riegl, B.M., Moyer, R.P., Morris, L.J., Virnstein, R.W. and Purkis, S.J. (2005). *Distribution and seasonal biomass of drift macroalgae in the Indian River Lagoon (Florida, USA) estimated with acoustic seafloor classification (QTCView, Echoplus)*. Journal of Experimental Marine Biology and Ecology 326:89-104.

Sabol, B, M, and Johnston, S, A. (2001). *Innovative techniques for improved hydroacoustic bottom tracking in dense aquatic vegetation*. Report ERDC/EL MP-01-2, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Sabol, B, M, Shafter, D, J. and Melton, E.M. (1996). *Mapping seagrasses for dredging operations*. US Army Corps of Engineers. Vol D-96-1.

Sabol, B. M., Melton, R.E., Chamberlain, R., Doering, P. and Haunert, K. (2002). *Evaluation of a digital echo sounder system for detection of submersed aquatic vegetation*. Estuaries 25:133-141.

Sabol, B, M, Kannenberg, J, and Skogerboe, J.G. (2009). *Integrating acoustic mapping into operational aquatic plant management: a case study in Wisconsin*. Journal of Aquatic Plant Management 47:44-52.

Schaffelke, B. and Lüning, K. (1994). *A circannual rhythm controls seasonal growth in the kelps Laminaria hyperborea and L. digitata from Helgoland (North Sea)*. European Journal of Phycology 29:49-56.

Schneider, P, Burczynski, J, and Monteoliva, A. (2001). *Results from submerged aquatic plant assessment using digital echosounder technique*. International Council for the exploration of the Sea Joint session of FTFB and FAST Working Groups 23-27 April 2001.

Simms, É.L. and Dubois, J-M. M. (2001). *Satellite remote sensing of submerged kelp beds on the Atlantic coast of Canada*. International Journal of Remote Sensing 22:2083-2094.

Sjøtun, K., Fredriksen, S. and Rueness, J. (1998). *Effect of canopy biomass and wave exposure on growth in Laminaria hyperborea (Laminariaceae: Phaeophyta)*. European Journal of Phycology 33:337-343.

Stekoll, M.S., Deysher, L.E. and Hess, M. (2006). *A remote sensing approach to estimating harvestable kelp biomass*. Journal of Applied Phycology 18:323-334.

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

Stepnowski, A., Moszyñski, M., Komendarczyk, R. and Burczyñski, J. (1996). *Visual real-time Bottom Typing System (VBTS) and neural networks experiment for seabed classification*. Proceedings of the 3rd European Conference on Underwater Acoustics. Heraklion, Crete. pp. 685-690.

von Szalay, P. G. and McConnaughey, R.A. (2002). *The effect of slope and vessel speed on the performance of a single beam acoustic seabed classification system*. Fisheries Research 54:181-194.

Werner, A. and Kraan, S. (2004). *Review of the potential mechanisation of kelp harvesting in Ireland*. Marine Environment and Health Series No. 17.

Winfield, I, J, C. Onoufriou, M, J, O'Connell, M, Godlewska, R, M, Ward, A, F, Brown, and Yallop, M, L. (2007). *Assessment in two shallow lakes of a hydroacoustic system for surveying aquatic macrophytes*. Hydrobiologia 584:111-119.

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