Modelling the potential distribution of *Zostera marina* in Wales.

Gregory David Brown

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Abstract
Predictive mapping of habitats within a GIS system is becoming increasingly widely used and is particularly useful in marine systems where in situ mapping can be time consuming and costly. This study focuses on the distribution of Zostera marina in Wales. This seagrass species forms meadows that are ecologically and economically important, despite this there is limited knowledge about its distribution. The aim of the study was to build a model that predicts the distribution of Z. marina and then test its predictive capacity relative to mapped and historical records of seagrass in Wales. A predictive habitat distribution model was created using prior information (publically available datasets) and the environmental characteristics (sediment, exposure, energy, slope and depth) of sites where Z. marina is known to exist. This model was tested against subtidal and intertidal surveys of areas around the Llyn peninsula. The predictive capacity across the four study bays was 0.466 (135 ha predicted and 63 ha of this within known meadows). A total of 4581 ha was predicted throughout Wales in 32 locations. Of these locations 12 are places where Z. marina has been studied or historical records of Z. marina presence exist. The habitat suitability maps produced during this study extend along the entire Welsh coast and can inform management and planning on a landscape scale. Application of directed sampling informed by the predictive model has been implemented to map a previously unknown meadow in Abersoch. There are 18 more areas where this could be applied, thus increasing the knowledge of Z. marina distribution in Wales.

Key words: Predictive mapping, Zostera Marina, Relative exposure index, Wales, Conservation planning.
Declarations and Statements

I, Greg Brown, state that the work submitted is in extent fully a result of my own investigations. A full bibliography is attached to this work, giving credit and any and all work that is cited within.

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Date ...............................................  

I, Greg Brown, declare that this work has not already been submitted or accepted in any substance for any degree, and is not being concurrently submitted in candidature for any degree.

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**Introduction**

Safeguarding marine habitats requires an understanding of their spatial distribution (Grech and Coles, 2010). Data about this is often limited and sometimes unavailable at broad (ecosystem) scale. The volume, accuracy and reliability of this data is much less in the marine environment compared to the terrestrial realm (Lathrop et al., 2001). Additionally at ecosystem and landscape scale mapping habitat distribution is both logistically difficult and expensive (Mckenzie, 2001). Data regarding habitat occurrence is usually in point format, this can have limitations especially when datasets are incomplete and effort/methodology related (Bekkby et al., 2008). Habitats that are dynamic and show temporal changes are often particularly poorly represented by point data (Kelly et al., 2001). Predictive habitat distribution models can overcome some of these limitations which is useful because mapping can be used for conservation planning. Predictive habitat models are increasingly being used to map the distribution of species due to the lack of resources to do this via other methods (Bekkby et al., 2008).

Seagrasses are marine plants that are found in shallow sheltered waters (Baily et al., 2002). In the UK there are two species of seagrass; *Zostera marina*, and *Zostera noltii* which are both native. There is limited knowledge about their distribution, therefore creating a model that predicts their distribution can be useful for conservation and management. Seagrasses globally are in decline and therefore need protection (Green and Short, 2003). This is often conducted at broad scales through marine protected areas (MPA) however these need to be informed by science showing why they are needed (Jennings, 2009). Predictive habitat mapping uses a quantified framework to display areas that may be important to protect and manage. They can also be conducted on a broader scale using less resources than traditional mapping (Lathrop et al., 2001). Finally they can account for the dynamic nature of seagrass (Merow et al., 2013).

**Physical factors effecting seagrass growth**

Seagrasses require specific environmental conditions to grow, understanding this is important because it can help protect them from anthropogenic impacts. Additionally with regard to modelling, physical factors must be incorporated into a model in order to describe seagrass distribution. Knowledge of the factors that influence seagrass growth at ecosystem scale already exists from other studies (Bekkby et al., 2008, Callaghan et al., 2015, Valle et al., 2013). This section summarises the environmental conditions that seagrass and specifically *Z. marina* need to grow.
**Depth and light availability**

Like all plants *Z. marina* requires sufficient light to grow and survive. In certain areas the compensation depth has been up to 10m (Bekkby et al., 2008). However generally in the UK it is found up to 5m depth when there is limited suspended sediment (Davison D, 1998). There is very little data about light availability/suspended sediment loads in inshore waters in the UK (Devlin et al., 2008). Depth can be used as a proxy for light availability (Valle et al., 2013) but light can be reduced by suspended sediment in higher energy areas and increased nutrients. Therefore using secchi depth data is more accurate, however this data is very limited in Wales (Greve and Krause-Jensen, 2005). Tidal amplification of light can occur by a factor of up to seven (Bowers and Brubaker, 2010). Another factor which can be important for seagrass presence and distribution is slope which can be seen as a function of change in depth. The effect of slope varies between species and studies. However regarding *Z. marina*, growth only occurs in gently sloping areas and is never present in areas steeper than 5.58° (Bekkby et al., 2008).

**Sediment**

*Zostera* requires sandy to muddy substrata (Davidson, 1998). Fine sand and mud are often sediments that are found in lower energy areas. Soft sediments are required because *Zostera spp.* have extensive root systems which can grow up to 20cm into the sediment (March et al., 2013). Seagrass beds can extend laterally into uncolonized sediment via rhizomatous spread (Larkum et al., 2006). Colonisation of areas is rare because sediment must be physically stable and have high levels of dissolved nutrients (Greve et al., 2005). Generally other organisms such as seaweeds need to be in the area to stabilise sediments. Seagrasses are a dynamic species and can become covered by sediments and die back (Kelly et al., 2001). Regrowth is possible if the rhizome remains.

**Disturbance/exposure**

*Z. marina* requires sheltered environments with very little disturbance from waves and wind (Davidson, 1998). Energy at the seabed comes from two main sources, and both can affect seagrass beds. The first is tidal current, which affects the water column and the character of the seabed. The second is wind generated wave energy which can increase suspended sediment and cause surface waves which in shallow water disturbs the seabed (McBreen and Askew, 2011). Intertidal *Z. marina* is particularly vulnerable to surface waves (Callaghan et al., 2015).
**Temperature and salinity**

The temperature range of *Z. marina* is between 5°C and 30°C (Davidson, 1998) and therefore is unlikely to be a limiting factor in Wales (average winter temperatures around 8°C and summer highs around 17°C). *Zostera* can grow and reproduce in full, variable, reduced and low salinity (Larkum et al., 2006). Salinity can affect growth and germination (Davidson, 1998) but is outside the scope of this model.

**Predictive mapping applications**

Predictive mapping can be an extremely useful tool for many reasons. Seagrass models have contributed to a better understanding of distribution and the factors involved in this (March et al., 2013). They can be used to aid planning, management and have even been used to relate seagrass presence to potential threats (Kelly et al., 2001). In the most part they are useful at broad scales where extensive sampling is impractical and not cost and effort effective. Predictive mapping can represent a broader spatial scale with regard to presence than any other method (Grech and Coles, 2010). Models extrapolate information from sampled areas to unsampled areas using predefined parameters (Lathrop et al., 2001). A key feature of predictive models is that they are quantitative and are defined objectively (Bekkby et al., 2008).

When mapping a dynamic species (such as *Z. marina*) it is important to understand that local extinctions and recolonization are frequent and the extent and distribution changes both seasonally and annually (Valle et al., 2013). Therefore traditional polygonal maps of surveys have limitations as they do not convey this dynamic nature (Bekkby et al., 2008). Predictive models represent the area which has the specific environmental parameters for seagrass growth, and shows areas where seagrass can grow even if it is not currently present in that locality (Lathrop et al., 2001).

Exposure plays a major role in the ecological structure of near shore environments and determining the level of exposure at sites can be challenging (Pepper and Puotinen, 2009). Data is not routinely collected at bays concerning the wind and waves that it experiences. Data can be collected using plaster of Paris tubes and alternative in situ measurement tools (Pepper and Puotinen, 2009). However this requires a long period of time to collect the data. In order to assess the exposure at different localities around the coast Relative Exposure Index’s (REI) are often used. They work by assessing the distance of uninterrupted water (fetch) from a site. More complex REI include information about wind strength and direction they also use unbound
fetch lines (will run to any area of land) unlike traditional lines that have a maximum fetch of around 10km. Data collection about wind in Wales is limited to two coastal weather stations (Anglesey and Pembray sands).

Figure 1 Traditional use of fetch lines (Pepper and Puotinen, 2009). More advanced REIs do not limit the distance of the tested fetch.

**Seagrass mapping in Wales**

Seagrass mapping is inherently difficult and time consuming (McKenzie et al., 2001). In Wales there are issues with visibility and cold temperatures. Due to these factors the accuracy and extent of mapping is generally quite poor. There is a need for finding new robust methods to allow effective planning and conservation.

Seagrass mapping in Wales has been focused on few well known locations such as; Skomer, Milford Haven and Porthdillaen with many other areas having little or no study. In a comprehensive report Kay Q, 1998 stated that only 5 meadows of substantial size are known in Wales (Milford Haven x 2, Skomer, Llyn X 2). Since this review was published there has been limited progress in locating new meadows. Areas such as Anglesey remain poorly mapped, in 2012 a new meadow was discovered by volunteer divers in Borthwen bay in Rhoscolyn (Greenhelgh, 2012). However there is only a small amount of presence data in this location with limited follow up work. Criccieth (Black Rock Sands) on the south coast of the Llyn was most recently mapped in 2002. A further study was conducted in 2005 when the tide was .7m, absence was reported because only an intertidal study was conducted (Boyes et al., 2008). It is likely that a meadow was present, but could not be seen during this survey. NRW have mapped the meadow at Porthdillean in 1997, 2004, and 2005. In this time there has been
a reported reduction of 58% (Boyes et al., 2008). The meadow at Porthdillean has had aerial photography with ground truth surveys conducted by volunteer divers. This does lead to areas where presence is unsure (as seagrass and algae (Ulva enteromorpha) look similar in aerial photography) (McKenzie et al., 2001).

Remotely sensed data can be extremely useful with regard to large scale mapping but only if there is a good sampling and verification process. The ability to incorporate data into geographical information systems (GIS) has led to increased accuracy and uptake of the methodology (McKenzie et al., 2001). However this has been very limited within Wales. Ground truth surveys of remotely sensed data has relied on volunteer divers where it has been conducted.

**Historical seagrass loss in Wales**

The Welsh coastline is an important resource for the country from environmental, economic and social perspectives (McInnes and Benstead, 2013). 2.5 billion pounds per year is generated from marine industries (WWF, 2012). There has been extensive coastal development, which has increased post industrialisation. Development includes; lagoon and marina developments, extraction from sand and gravel pits, as well as emerging industries such as wind and wave energy exploitation (Henriques et al., 2015). There has been extensive fishing pressure around Wales, particularly the oyster fishery which used to be extensive. Oysters are now rare due to the combined effects of pollution and overfishing (Kershaw and Campos, 2011).

Wales displays similar trends as the rest of Europe with declines in seagrass abundance since the early 19th century (Christiansen et al., 1981). This has been attributed to a variety of causes, including Zostera wasting disease, which was prevalent during the 1920’s and 30s. It is thought that increased temperatures reduced metabolism and consequently the ability for Zostera to deal with the disease (Christiansen et al., 1981). The result was a mass die back of seagrass, and affected areas are slow to recover (van Katwijk et al., 2010). The extent of damage is not well known as seagrass was poorly mapped before the disease struck. Estimates of loss in Wales has been based on extrapolation of data from parts of south England (Bockelmann et al., 2012). As the human population has increased there is also increasing pressure caused by eutrophication and other human induced pressure (Valle et al., 2013).
Aims
This study focuses on the distribution of *Z. marina* in Wales at the landscape scale and how this can be predicted using environmental variables. The aim of this study is to generate and test a predictive habitat model using GIS to show locations that have the suitable physical parameters for *Zostera* growth (exposure, sediment type, water depth and slope) and then test the predictive capabilities using ground truth surveys. The following hypotheses will be tested: (1) Can modelling predict the distribution of *Z. marina* around Wales? This will be examined by comparing model outputs to historical data and ground truth surveys. (2) At the scale of a bay how well can models predict *Z. marina* distribution? Models will be tested against survey data in four experimental locations. (3) How can modelling be applied to planning and conservation?
Method
ArcGIS (ESRI version 10.3) was used to create a predictive habitat distribution map for *Z. marina* distribution in Wales. This was created using a range of existing data sources about environmental variables such as; wind, bathymetry, substrate and tidal current energy. Additional data collection of *Z. marina* was conducted around the Llyn peninsular, Wales.

Study Site
Wales is in the south-western region of the UK and borders; England, the Irish Sea, Cardigan Bay, St Georges Channel and the Bristol Channel. South westerly winds dominate for most of the year. For the purposes of this study the coastline has been divided into two sections (north and south). The coastline of Wales is 2740km long (WWF, 2012), therefore mapping it is practically and economically difficult. There are two species of seagrass found on the coast *Z. marina* and *Z. noltii*. Certain meadows have received extensive study such as Porthdillaen, Skomer, and Milford Haven whereas in other areas there are only historical records of presence such as Oxwich. Natural Resources Wales (NRW formally Countryside Council for Wales (CCW)) holds 928 records of reported presence points around the UK. The error range varies from 100m to 10km in publicly available records. For this study data was obtained from NRW that contains Global Positioning System (GPS) latitude/longitude with 5m error. Historical data has been summarised by (Kay Q, 1998) with data collection from county records and other key sources. Many regions still remain unsurveyed. A particular issue within the UK dataset is the lack of absence data whereas in other countries this is recorded (Grech and Coles, 2010).
Figure 2 the known extent of Seagrass in Wales. ++ Records represent meadows that have been mapped and have positive species ID. + Records represent points that are certain but may be unmapped. ? Records are historical records that have been reported but there is no further evidence and species may not have been recorded.

Data collection
A range of sources were used to establish what is already known about the distribution of *Z. marina* in Wales (summarised in table 1). Locations where *Zostera* leaves were found were not used to inform the model because there is evidence that they can travel large distances and washed up leaves may not represent an offshore meadow (Kay Q, 1998).
Table 1 the range of data that was used to inform and test habitat map. Data requests were made from NRW (see forms in appendix)

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<td>Botanical Society of Britain and Ireland</td>
<td>Seagrass presence (points only)</td>
<td>To inform model</td>
</tr>
<tr>
<td>Seasearch</td>
<td>Seagrass presence (points only)</td>
<td>To inform model</td>
</tr>
<tr>
<td>Marine Conservation Society</td>
<td>Seagrass presence (points only)</td>
<td>To inform model</td>
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<tr>
<td>Joint Nature Conservation Committee (JNCC)</td>
<td>Seagrass presence (points only)</td>
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<td>South East Wales Biodiversity Records Centre</td>
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<tr>
<td>Skomer Marine Reserve</td>
<td>Detailed maps of seagrass presence (polygon and points)</td>
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<tr>
<td>Milford Haven EIA (Nagle, 2013)</td>
<td>Detailed maps of seagrass presence (polygon and points)</td>
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<tr>
<td>(Unsworth, unpublished)</td>
<td>File scale seagrass meadow mapping</td>
<td>Model testing</td>
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**Environmental variables**

Environmental variables were selected a priori as explanatory variables of *Z. marina* growth (March et al., 2013). The variables were; geomorphological variables (depth and slope), and oceanographic variables (Energy at the seabed, sediment type and relative exposure (RE)). These variables are regularly cited as the key determinates of seagrass presence (Bekkby et al., 2008).
Table 2: the environmental variables that were utilised to build the habitat prediction map.

<table>
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<td>SeaMap JNCC (McBreen and Askew, 2011)</td>
<td>Vector data set of EU substrate types</td>
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<td>Tidal and Wave Energy</td>
<td>Hydrodynamic forces are a physical driver of distribution.</td>
<td>SeaMap JNCC (McBreen and Askew, 2011)</td>
<td>Vector data set of EU. All ocean areas divided into 3 energy classes (low, moderate, high)</td>
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<td>Bathymetry</td>
<td>Depth controls the light that is available for photosynthesis</td>
<td>General bathymetric chart of the oceans (GEBCO)</td>
<td>Geotiff Raster data at 30 arc second interval grid. Resolution of 0.518km²</td>
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<tr>
<td>Relative Wave Exposure (REI)</td>
<td>Hydrodynamic forces are a physical driver of distribution.</td>
<td>RenSmart (Wind), World vector data set. USGS wave fetch model.</td>
<td>RenSmart text file with wind speed, direction (16 points) and power as %, Data from 2000 to 2014. Raster generated by wave fetch. 3km² grid squares</td>
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Further information about environmental data

Data about substrate type was not comprehensive and many intertidal and shallow areas had no data (McBreen and Askew, 2011). Therefore it was not possible to select for soft substrate instead hard substrate was used to exclude areas. Additionally the energy classes in the SeaMap data were only broken into three classes which is relatively course and does not account for some of the variation that is important for seagrasses (McBreen and Askew, 2011). REI was used to give a more accurate representation of wind induced wave exposure. The REI exposure model had relatively large processing times which limited the resolution. Additionally bathymetric data obtained from GEBCO had a relatively course resolution (see table 2).

Relative Exposure Index

A fetch model was created in ArcMap using the United States Geological Survey (USGS) wave fetch software. The software creates an exposure score based upon distance from nearest land mass and wind direction (fetch). It then also calculates a weighted fetch based upon % of the year that wind comes from each direction (Rohweder et al., 2012). Using a 14 year dataset from RenSmart gave a good temporal representation of wind. Separate wind data was used for south and north Wales analysis, due to differences in prevailing wind conditions (see figure 3). Each of the 16 wind directions is given an additional 9 radials on 3° axis from the originals. This
methodology is widely used in shore protection work and has been found to represent more real world conditions (Rohweder et al., 2012). The average fetch distance is taken from this. If REI exposure models are set incorrectly (wrong fetch distance) this can reduce the sensitivity of the model (Pepper and Puotinen, 2009). Therefore a global vector shoreline was used in analysis to eliminate the possibility of error.

![Figure 3 wind roses showing the variation in wind direction in south Wales (left) and north Wales (right).](image)

**Model Creation**

Known *Z. marina* locations (from data sources displayed in table 1) were compared with geomorphological and oceanographic variables (shown in table 2). Environmental conditions that occurred in areas with confirmed reports with high certainty were included in the model. Using these variables four models were created for comparison; (1) REI and depth, (2) SeaMap (energy) and depth (3) REI, depth, SeaMap (energy) (4) REI, Depth, SeaMap (energy) and slope. All models had exclusions (using erase function) from SeaMap hard substrate.

All geoprocessing and analysis was conducted in ArcMap 10.3 using the British National Grid coordinate system. Model 1 was created using an intersect function between areas of up to 6 on the REI scale and depth of up to 5m. Data was converted into vector format prior to this. Model 2 was created using the intersect tool for all values that had low and moderate energy and fell within areas up to 5m in depth. Model 3 was created in the same way, but with an additional intersect layer of REI up to 6. Model 4 was created by using all the before layers and the slope
function (i.e. amount of change in depth between tiles). An erase function was used to remove all areas of hard substrate (all models).

**Ground truth surveys**
Seagrass surveys were conducted between 03.06.2015 and 13.07.2015. The survey had two major components; intertidal and subtidal. Six bays were selected for surveying; Porthdillaen, Abersoch, Llanbedrog, Pwllheli/Aberech, Pen y Chain and Criccieth. Further studies were carried out at Pen y chain and Porthdillaen using a similar methodology (Unsworth, unpublished) and was utilised for analysis.

The following parameters were collected for subtidal and intertidal surveys: position (GPS) (obtained using Garmin GPSmap 62stc and GPSmap 62), seagrass presence/absence, algae presence/absence, substrate, notes/other features. Substrate was recorded using the adaptation of the Folk method that has been used by UkSeaMap (McBreen and Askew, 2011).

**Subtidal sampling details**
A small 2m inflatable RIB was used with 3 observers (2 on boat, 1 snorkeler) (Mckenzie, 2001). The boat moved along transects. Additional points were sampled between transects to check habitat continuity (Rasheed, 2003). Sites were examined by free diving observers swimming to the bottom. Seagrass meadow boundaries were determined by continuing transects until three successive points indicated absence (Rasheed, 2003). Search patterns were widened when it was clear that points were in the centre of the meadow and narrowed when coming close to the edge (McKenzie et al., 2001).

**Intertidal sampling details**
Mapping began from the high tide line. Transects were walked parallel to the shoreline, with the observer marking waypoints on a GPS approximately every 10 to 20m. The low tide line was walked at the time of low tide, differences in tidal height did not need to be accounted for because subtidal work covered the boundary at all survey locations.

**Model analysis**
Analysis will be conducted on two scales, broad (landscape) and fine (bay) scale. Broad scale analysis will compare model predictions with historical data and data from ground truth surveys. It will look at regions as a whole, and variation between the models will be explored.
in relation to the driving factors. Fine scale analysis will compare point data gathered in ground truth surveys with the predictive habitat distribution models. The ability for the model to predict habitat area within a bay will be assessed. A predictive capacity value will be generated by assessing how well the model matches with surveyed data at four bays. The model predicted area that overlaps with known area will be divided by the total predicted area to give the predictive capacity. This analysis will only be conducted for the Llyn peninsular.
Results
Four predictive habitat models were generated according to different parameters. Figures 4, 5, 7 and 8 show the predicted habitat areas according to each model. Model 1 predicts the highest area of 22353 ha and model 4 predicts the least of 4581 ha (all of Wales) this is a reduction factor of 4.87. The coast of north Wales has a predicted area of 3995 ha and south Wales has 546 ha.

Anglesey

Figure 4 predicted extent of *Z. marina* under different model conditions in Anglesey: (1) REI and depth (8978 ha), (2) SeaMap energy and depth (8643 ha), (3) SeaMap, REI and depth (6524 ha) and (4) SeaMap energy, REI, depth and slope (2459 ha). This is a reduction value of 3.65.
There are seven key areas predicted in model 4. Bodorgan bay on the south western part of Anglesey is an estuarine area that has predicted seagrass presence (all models), this area has had no previous records. The main predicted area around Holyhead is Penrhos, which is extremely sheltered by the two islands in an area commonly known as the inland sea. There are reports of extensive meadows in this area from an intertidal survey in 1990 by CCW (Kay Q, 1998). More specifically presence has been reported around the four mile bridge (Jones, 1968 in Kay Q, 1998). On the north west of Anglesey there is predicted areas at Porth y Bribya and Church bay. There has been records of Zostera presence in the west of Anglesey however there has been little study of this (Kay Q, 1998), it is possible that unmapped meadows are present. On the east of Anglesey there are predicted areas at Dulas Bay and Red Wharf Bay however there are no reported records or surveys in this area. Finally there are extensive areas predicted around Trwyn y Penrhyn and more broadly throughout the Menai Straits which corresponds to mapped records from 2004/05 by CCW (Boyes et al., 2009). There are several records of presence in this area, however there has been limited recent study.

Variation between the models can mostly be explained by the incorporation of the slope layer. It reduced the area around Holyhead and the Menai Straits much of which have steeply sloping regions which is unsuitable for seagrass growth. The resolution of the UK SeaMap means that the high tidal current in the Menai Straits is not accounted for. Additionally the resolution of the REI means that this area was not analysed effectively. However the wind driven exposure in the straits is likely to be extremely small.
Llyn peninsula

Figure 5 Predicted extent of *Z. marina* under different model conditions around the Llyn peninsula: (1) REI and Depth (5620 ha), (2) SeaMap energy and depth (3629 ha), (3) SeaMap energy, REI and depth (2284 ha) and (4) SeaMap energy, REI, depth and slope (1256 ha). A reduction factor of 4.47.

There are seven key areas of predicted habitat around the Llyn (model 4). Trefor on the south side of the Llyn has habitat area predicted, this area has records of *Z. marina* in small patches on offshore reefs (Seasearch 2012) thought to be propagules from Porthdillaen. Porth y Nant (3km SW from Trefor) has a small area of suitable habitat predicted however there are no records of presence here. Porthdillaen is predicted, which is a well-known and mapped meadow (see figure 9). Abersoch bay on the north of the Llyn was predicted, previous to this study there had been presence reported in county flora records (Griffith, E, 1895 in Kay Q, 1998), ground truth surveys testing the model found a meadow there (see figure 9). 4km to the east of Abersoch is Llanbedrog which had a predicted habitat area, there is no previous evidence of a
meadow at this locality only of drift material (Kay Q, 1998). Pwllheli was predicted in all models, presence has been noted in this location by (Griffith, E, 1895 in Kay Q, 1998) however *Z. marina* is no longer found in the bay (not found during ground truth surveys). Finally the model predicted an area at Criccieth on the south coast which has previously been mapped (Boyes et al., 2008) and was sampled during this survey (See figure 9).

Variation between the models around the Llyn is largely as a result of incorporation of the REI layer. It reduces the predicted habitat area around Aberdaron (model 2 predicts presence). However the REI shows this area experiences high levels of wind driven wave exposure. As with Anglesey slope also eliminates areas, specifically around Llanbadrog and Abersoch.

**Fine Scale Analysis**

The ground truth survey dataset contained a total of 2715 observations. 1348 of which represent presence of *Z. marina* and 1367 of absence.

Figure 6 comparing the predicted habitat distribution with field measurements from ground truth surveys.
**Porthdillaen**
Ground truth surveys conducted during this study have estimated the current total extent of seagrass bed in Porthdillaen to be 16.51 ha. This compared to an estimate of 26.55 ha by CCW/NRW (Boyes et al., 2008). The UK SeaMap model predicted an extent of 155.22 ha in the bay and the REI, Depth model predicted 156 ha. Out of the area surveyed in this bay absence was recorded in 16.23 ha of the model predicted area.

**Criccieth**
Ground truth surveys have estimated a total extent of 17.54 ha at Criccieth. However the area is very sparse and unlikely to be continuous within some of this area. The area could also be higher as only 86 points were taken at the location. All models predicted a 15.97 ha area in the bay, however slightly offshore from the meadows current location (no crossover 12m away at closest point).

**Abersoch**
A meadow of approximately 3.8 ha was found and mapped in Abersoch for the first time during this study. The extent of the meadow could be up to 41 ha (based on unmapped area surrounding the mapped area (see figure 9). The model predicted a suitable habitat area of 162.43 ha. Ground truth surveys showed that the sediment is unsuitable in the nearby area of Llanbadrog and the eastern side of Abersoch.

**Pen y Chain**
The extent of the meadow at Pen y Chain has been estimated at 16.73 ha (Unsworth unpublished). It was not predicted by the model in this area due to bathymetry of -7m. This is due to bathymetry being inaccurate. Surveys showed this area to be shallower. The REI at lowest resolution showed most of the area has an REI exposure of 0 (no exposure). There was 1.36 ha outside this area in a higher exposure of 7. Prior data had only shown a REI of up to 5, this area was newly mapped and lives outside the previously known range of exposure.
Figure 7 predicted extent of *Z. marina* under different model conditions in Pembrokeshire region (1) REI and Depth (1873 ha), (2) SeaMap energy and depth (3336 ha), (3) Seamap energy, REI and depth (989) and (4) SeaMap energy, REI, depth and slope (488 ha). A reduction factor of 6.83.

The majority of the areas around Pembrokeshire that are outside Milford Haven and predicted by the model have not been assessed. These include Fishguard, Newport Bay, Little Haven and Saundersfoot. Dale (predicted by all models) has records of presence, but is now thought to be extinct (Kay Q, 1998). Areas within Milford Haven match with known records (Gelliswick, Littlewick and Bullwell bay) (Kay Q, 1998, Nagle, 2013).
Figure 8 predicted extent of *Z. marina* under different model conditions in Glamorgan; (1) REI and Depth (4599 ha), (2) SeaMap energy and depth (8390), (3) Seamap energy, REI and depth (3350 ha) and (4) SeaMap energy, REI, depth and slope (98 ha). A reduction factor of 85.61.

All models predict habitat suitability in the Burry Inlet, there is a well-studied bed of *Z. noltii* in the area (Mazik and Boyes, 2009) but it is unlikely that *Z. marina* is present due to poor water quality resulting from a strong tidal regime. All models predict suitable habitat areas within Swansea bay. Models with slope and REI predict it more in the western side of the bay which is consistent with historical reports of *Z. noltii* (Kay Q, 1998) however it is deemed very unlikely that a population still persists. Other key areas around the east Glamorgan coast include; Dams bay and Watch-House bay neither of which have any recorded presence and do experience a high tidal range and suffer from low light availability (Kadiri et al., 2013). In addition Sully Island and Penarth are predicted by all models and have historical records for
presence (Stonie, 1886 in Kay, Q. 1998) very little is known about the current extent and if there is presence in this area.

Models that incorporate REI show much less extent around the Gower peninsula this is because wind driven wave exposure is very high along much of this coast (exceptions include sheltered bays such as Oxwich). There is also a large tidal range throughout the area. Models incorporating SeaMap predict less extent around Glamorgan, this is because it includes tidal energy which is very high in this region (12.3 mean spring) (Ports, 2015). Furthermore slope reduces the predicted extent by 3252 ha (from model 3) and is the main reduction factor.

**Model testing**
The model was tested against ground truth surveys where 2715 observations were made. The areas sampled and mapped are shown below in figure 9. The highest predictive capacity model was 4 (which incorporated all environmental variables). Predictive capacity figures for all models are shown in table 3.

Figure 9 extent of seagrass presence/absence seen on ground truth surveys. Polygonal areas were generated around presence points.
Table 3 model predictions compared with projected areas based on data collected during ground truth surveys. Dividing the area that was correct by extent predicted (within the study bay) gives the predictive capacity.

<table>
<thead>
<tr>
<th>Model type</th>
<th>Predicted habitat extent in study bays (hectares)</th>
<th>Area that intersects with presence in known bays (hectares)</th>
<th>Predictive capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) REI and Depth</td>
<td>511</td>
<td>152</td>
<td>0.297</td>
</tr>
<tr>
<td>(2) SeaMap energy and depth</td>
<td>456</td>
<td>133</td>
<td>0.291</td>
</tr>
<tr>
<td>(3) SeaMap energy, REI and depth</td>
<td>299</td>
<td>61</td>
<td>0.204</td>
</tr>
<tr>
<td>(4) SeaMap energy, REI, depth and Slope</td>
<td>135</td>
<td>63</td>
<td>0.466</td>
</tr>
</tbody>
</table>

**Environmental parameters**

Environmental parameters were compared against ground truth surveys to determine the ranges that seagrasses are known to grow in. These findings are independent from model construction. The average depth *Z. marina* was found in was 3.4m with the minimum being intertidal (Above chart datum) and maximum of -5m. The average exposure (REI) was 0.07 with the lowest being 0 and the highest being 7 (Scale of 0 to 64).
Discussion
The model outputs from this study display areas which have the most important environmental parameters for seagrass growth. Model outputs represent a predictive habitat distribution and represent areas where it is physically possible for *Z. marina* to grow. Testing the model against known locations only gives part of the picture as the model shows areas of potential growth and cannot predict areas of actual growth. Knowing areas of potential growth is useful for planning and conservation, because *Z. marina* and seagrasses in general are dynamic and can colonize new areas as well as be lost from others on a yearly basis (Valle et al., 2013). This also limits the ability to test a model without long time series data. Conceptual modelling is a useful approach for understanding seagrass systems (Grech and Coles, 2010) and this study represents the first time this has been attempted in Wales.

The models created in this study have been shown through ground truth surveys to have errors of commission. There are three main processes that could cause this; historical seagrass loss, small scale factors (sediment stability/nutrients, propagule distribution) and limitations in the model. The level of seagrass loss in Wales is uncertain and is explored below. Small scale factors will always be difficult to account for within a modelling framework, but can be considered when analysing and drawing conclusions from results. Model limitations include; no flood plume modelling, inaccuracies in bathymetric dataset and the effects of pollution and other anthropogenic impacts.

### Historical seagrass loss

The absence of long time series and historical data means there is limited understanding of *Z. marina* distribution in Wales. It has been widely recognised that there have been declines in abundance of *Zostera* in the UK (Bockelmann et al., 2012). This is often attributed to wasting disease which occurred during the 1930’s (Short and Wyllie-Echeverria, 1996) and was thought to cause extensive declines in distribution. Much of this information is extrapolated from the south coast of England and the Isle of White (Bockelmann et al., 2012), in situ studies of Wales populations did not occur. Therefore the amount of *Zostera* that was lost is hard to quantify. More recently there have been concerns with anthropogenic impacts such as eutrophication, anchor/mooring scars, bottom trawling and dredging. Pollution is a particularly important issue within Wales. Many of the predicted sites (Swansea Bay, Barry Island and Anglesey) have had extensive industry and pollution issues (WWF, 2012) which could have resulted in declines in seagrass distribution. Only meadows that have been mapped consistently can be used to show
declines and even when this occurs variation in methodology and effort affects results. CCW have reported a 58% decline in Porthdillaen between 1997 and 2004 (Boyes et al., 2008) however examples in other areas are lacking. Modelling can provide an insight into past distribution and show the possible extent of loss. It can also be used to inform decision making for conservation planning and future restoration programmes (Lathrop et al., 2001).

**Anglesey**

Anglesey has received very limited study with regard to seagrass distribution (Kay Q, 1998) therefore modelling can be a very useful tool to plan future surveys and make informed decisions. It is likely that the predictive habitat model has compensation errors in this region due to factors that are outside its scope.

**The inland sea**

Each model predicts seagrass within this area, although the extents vary between models. The largest predicted area is 1111 ha (model 2 SeaMap and Depth) and the lowest was 43 ha (model 4 all parameters included). Slope had the greatest effect on distribution with many of the areas having a steep slope in the region. The REI exposure is low due to protection offered on either side from land. High resolution REI had to be conducted for this region. Lower resolution raster datasets would not incorporate Holyhead as a land mass. Many anthropogenic impacts have occurred in this region which may affect seagrass distribution including the Stanley Embankment. These impacts have changed the tidal regime and could not be accounted for in the model.

**North west Anglesey**

All models predicted small habitat areas in the north west of Anglesey (Porth y Bribya and Church bay), this is largely because they are sheltered from prevailing winds and consequently have a low exposure value. Holyhead is the main reason for this shelter. This area has not been surveyed however there is historical presence in Cemlyn Bay which is 5.3km away and likely to experience similar environmental conditions.

**East Anglesey**

There is an extensive area (1276 ha model 4) predicted on the eastern side of Anglesey. This area is sheltered with regards to wind generated waves, however it does experience strong tidal currents with a tidal range of 8.22m (mean spring) (Ports, 2015). High tidal energy is a key
factor in determining seagrass distribution (Grech, 2009). In addition there are many anthropogenic impacts that may have reduced the ability for seagrass to survive in this region. The area is in close proximity to Liverpool bay which has inputs from the; Conway, Ribble, Clwyd, Mersey and the Dee which have all previously had metal contamination issues (Bricheno et al., 2014). Heavy metals such as; Cadmium, Copper, and Lead can be toxic to seagrass (De Casabianca et al., 2004, Choi et al., 2005). Therefore the presence of seagrass is likely to be dependent on factors related to the plume of those rivers, particularly with respect to flood plumes. Flood plume modelling from rivers was not conducted in this study due to increased complexity and because very high resolution data and model runs are required to gain meaningful results (Bricheno et al., 2014). River plumes in Wales are likely to have detrimental impacts on Z. marina not only due to the contamination issues but also eutrophication (Burkholder et al., 2007) and the reduction in light attenuation (Grech, 2009).

There has been extensive Copper exports from the north east of Anglesey, Copper is toxic to seagrass (Choi et al., 2005). Historically there has been gravel extraction and land reclamation which leads to poor light attenuation, along with centuries of pollution and fishing (WWF, 2012). All of these factors have negative implications for seagrass and may have reduced extent and distribution. Further investigation is needed at areas where the model has predicted seagrass.

**Menai Straits**

There is 833 ha (model 4) of predicted habitat area in the Menai Straits. The area is essentially a submerged valley and is 25km in length (Boyes et al., 2009). It is very sheltered and is shallow throughout. There are differential tides in the area, which leads to high current flow and high suspended sediment loads (Dennison et al., 1993). In the modelling process depth is used as a proxy for light attenuation but does not account for changes in light attenuation due to suspended sediment loads (Greve and Krause-Jensen, 2005). This limits the predictive capacity of the model. Secchi disk data could be used to improve the model (Devlin et al., 2008), however long time series/baseline data is required which is currently unavailable.

**Llyn peninsula**

There are three well surveyed seagrass meadows around the Llyn peninsula, however outside of these areas have received very limited study (Boyes et al., 2008). Using the predictive habitat
model to inform surveys during this study allowed a previously unmapped meadow at Abersoch to be mapped. It is possible that there are further meadows like this that are still undiscovered.

**Pen y Chain**

Perhaps one of the most important and noticeable errors in all the model outputs was the predicted absence at Pen y Chain. This area has previously been mapped (intertidal only) (Boyes et al., 2008), and has been extensively mapped as part of this study. There are several reasons which could explain the presence of seagrass here, which were not accounted for in the modelling process. Firstly it has been reported that there is an offshore reef (SeaSearch 2015). There is evidence that shows waves lose much of their energy on the leading edge of a reef (Puotinen, 2005) which would reduce exposure to waves. Furthermore there are three submerged peninsulas below the Llyn which offer protection to this part of the coast (waves after this point will be fetch limited). Wave modelling that accounts for bathymetric data would be needed to account these variables in a habitat distribution model. The REI not accounting for bathymetry is a key limitation (Valle et al., 2013). Furthermore REI ignores shallow water processes such as shoaling, refraction, and diffraction (Hill et al., 2010). The REI does calculate weighted fetch values which is an advantage of this method (Rohweder et al., 2012).

Although not accounting for the additional shelter at this location may have reduced the size of the predicted meadow. The reason for the model predicting absence at this location is due to bathymetric data. The chart reported the depth as 7m and selection criteria was set with a maximum depth of 5m. However ground truth surveys showed the area to be shallower than this. The GEBCO dataset is the best publicly available however it still also has a course resolution and this site represents an error in the inshore region.

**Porthdillaen**

All models predicted an extremely extensive bed in Porthdillaen with extents ranging from 155.22 to 306.28 ha. NRW have estimated the area to be 28 ha (Boyes et al., 2008). Ground truth surveys estimated a smaller area of 16.52 ha. Porthdillaen represents one of the most studied meadows in Wales and falls within a Special area of conservation (SAC). The differences between predicted area and actual area could be caused by many potential factors. Model errors include not accounting for areas with rocks, rocky outcrops contribute to 16 ha of absence within the predicted zone. This is a limitation of the UK SeaMap data as it did not
extend all the way inshore (McBreen and Askew, 2011). Additionally the REI does not account for the full extent of protection offered from the headland.

Anthropogenic degradation is a key factor in determining seagrass distribution at this site. Physical degradation occurs from several sources such as tractors pulling boats on the upper shore and mooring, boat scouring and anchor scars on the lower shore a sub tidally (Boyes et al., 2008). Other factors that could possibly be contributing to degradation at the site include run off from the nearby Golf course and an altered sediment regime due to construction in the area (RNLI, 2015). However this has not been assessed.

**Criccieth**

The meadow at Criccieth is the final meadow that is studied by NRW in the Pen Llŷn a’r Sarnau SAC, because it is only revealed by equinox tides and is largely subtidal it is difficult to map (personal observation). Additionally it is very sparse so finding the edge can be challenging (Boyes et al., 2008). It was reported as absent in 2002 (Boyes et al., 2008). More recently the current study mapped an estimated extent of 17.54 ha, it is possible that the area is particularly dynamic, which highlights why having a predictive habitat distribution model can be useful. The model predicts an extent of 15.79 ha, this is a more useful figure than in situ mapping which is somewhat subjective according to effort/methodology due to the sparse nature of the meadow. Figure 6 shows that the mapped meadow and the habitat model have similar shapes. The reason for it being long and thin appears to be because the wave energy is too high for it to survive in the intertidal zone and depth limits its distribution further out. Predictive modelling has allowed us to understand these as the driving factors of the meadow shape. This area does have higher exposure than other areas around the Llyn (Porthdillaen and Pen y Chain), this may explain why the meadow is sparser however this requires further study.

**Abersoch**

A habitat area was predicted by all model outputs. Throughout the whole bay the area was 184 ha (model 4). In 3.8 ha of this area *Z. marina* was present. Due to lack of sampling effort in this area, the possible extent could be greater however this requires further study. The presence of seagrass in this meadow shows how modelling can be used to inform sampling, in areas that are unmapped. Potential areas can be surveyed with greater efficiency. Other areas around Abersoch were surveyed such as Llanbadrog and were found to have course gravel and rocky sediment. This was not shown on the SeaMap data and explains why the predicted area is
greater than the current known extent. It is still possible that there has previously been a meadow in Llanbadrog as there are reports of cast up in 1997 (Kay Q, 1998) but this could have come from Abersoch.

When comparing the output of the model at a small scale (bay scale) with data from ground truth surveys several model weaknesses are highlighted. These include the raster data being too coarse to show small areas of variation which can have a large effect when looking at the scale of a bay. Surveys also showed how sediment types can differ drastically within a bay. Fine scale sediment data is not available to incorporate into the model.

**Pembroke**

The most extensive seagrass beds in the Pembroke area are situated within Milford Haven. And they represent the best mapped seagrass in the area. Outside of Milford Haven there are well studied meadows around Skomer (Newman, 2011). Meadows in Milford Haven have the lowest exposure in Wales (see supplementary data). Model 4 predicted 53 ha in Milford Haven, 49 ha of this is in the Gelliswick and Littlewick bay areas. A further 4 ha is predicted around Dale in an area where the seagrass is reported to no longer exist despite reliable historical records (Kay Q, 1998). This is likely to be because of anthropogenic impacts. Milford Haven has had substantial development in recent years and is a busy port (Nagle, 2013). There are also issues with high nutrients loads in the area (Jones, 2014).

Outside of these areas there has been little study into *Zostera* distribution. However modelling has shown that there are many additional regions that have suitable environmental parameters for growth including; Saundersfoot (110 ha predicted, model 4) which faces the same direction as Swansea bay (has historical seagrass records) and has an extended headland which will offer protection from waves. Additionally there is shelter from prevailing winds afforded by Caldey Island. 36 ha (model 4) was predicted in Little Haven in the south east corner of St Brides Bay. This area has no previous records, however has a REI of 1 along with being a soft sediment area and it is well known for having good visibility/light attenuation. These areas are less industrialised than Milford Haven and consequently are likely to experience less environmental degradation. Key areas predicted by model 4 should be surveyed in the future, there is a good chance that further undiscovered meadows exist in the region.
Glamorgan

Model 4 predicts an area of 98 ha around the coast of Glamorgan, this is the lowest amount predicted for all the regions in Wales (compared to Anglesey, Llyn and Pembroke) despite the fact that it is the largest area considered. This is because much of the coastline is more exposed to long fetch from the Atlantic shown by REI values and areas around the Bristol Channel have a large tidal range shown by SeaMap values. Tidal range and exposure are the main limiting factors of seagrass growth (Grech and Coles, 2010). No ground truth surveys were conducted during this study for areas around south Wales. However models predicted potential habitat areas that have not been surveyed. Perhaps most importantly in the area around Sully island and Barry (see figure 8) where (Kay Q, 1998) suggested there could be presence of Zostera sp.

It is more likely that it will be Z. noltii in this location because of tidal movement reducing light attenuation. Further surveys are required to see if there is seagrass in this area.

All models predict habitat area in Swansea bay. The environment here could be suitable as the bay is shallow, gently sloping and sandy. There are historical reports of Z. noltii in the bay (Howells B, 1988 in Kay Q, 1998) however it is now deemed very unlikely that it is present. This is mainly due to the extensive anthropogenic impacts in the area which include; Copper mining/processing, scallop dredging, dredging for shipping channels, port developments and eutrophication from pollution (Kershaw and Campos, 2011, WWF, 2012). In this instance the predictive model can be seen to show the area of seagrass that has potentially been lost. All models predict presence in the Burry Inlet, where a well-studied Z. noltii meadow lies (Stillman et al., 2010). It is unlikely that Z. marina would survive in this location due to the suspended sediment load in this estuarine area (Mazik and Boyes, 2009). However model predictions do agree with the known extent of Z. noltii in the meadow.

In the Glamorgan region there is a lack of prior data informing the model (see figure 2). There are no known and well-studied Z. marina beds. Therefore prior data informing the model was obtained from Milford Haven. If any meadows are found and mapped in Glamorgan a model utilising more accurate priors could be used. The REI does not appear to account for acute storm events which occur in this region. Areas around Barry can receive very large waves during the winter months which would be detrimental to Zostera growth.
Model comparisons
Four models were used to predict habitat distribution in this study. They each included a different set of environmental variables and consequently had different outputs. Fine scale analysis showed that model 4 which included all the environmental parameters had the highest predictive capacity. This shows that slope is an important environmental parameter and has a reduction factor of 2.2 in addition to improving predictive capacity (.466 as compared to .204 without). Previous studies have disagreed about the importance of slope, but evidence from this study supports the argument that gentle slope is a requirement for *Z. marina* growth (Infantes et al., 2009, Lathrop et al., 2001). The lowest predictive capacity was the model that did not include SeaMap data (tidal energy information). This is consistent with the literature which shows tidal and wave energy to be the dominating factors of seagrass (Grech and Coles, 2010). The model could therefore be developed to incorporate more accurate tidal data in the future.

Predictive capability
Fine scale analysis showed that resolution of raster data was the dominating factor within the scale of a bay. At this scale predictive modelling has limited use for predicting the area present. However at broad scale the model has been used to find new, unrecorded meadows. It also shows distribution within a quantified framework which gives weight to assumptions about presence in new areas. This is particularly true in areas where historical records have been found but further study has not been conducted. There is still the issue of variable small scale factors which severely affect the distribution of *Z. marina* in the UK. Also biological processes are significantly more complex than that of the physical system (Callaghan et al., 2015) and therefore cannot be incorporated into the model. Despite this at ecosystem scale the predictive habitat model can be used to target surveys and resources. It can also be used for planning and justifying conservation because it is a quantifiable system that is informed by known and testable parameters.

Environmental parameters
Results show that the exposure and depth are the key limiting factors for seagrass in Wales. There are relatively few areas where depth, energy and slope are all within the correct ranges to allow growth. However unaccounted for environmental issues particularly anthropogenic impacts reduce the predictive capacity of these parameters. Areas of predicted presence such as Pwehelli harbour may have the right set of parameters but have been adversely affected by
anthropogenic impacts (development). A future model development could be to include a graded scale of anthropogenic impacts for all key sites around the coast.

**Applicability for restoration studies**

Predictive mapping can be used to show areas that have the right environmental parameters for seagrass growth, but may not currently exhibit a meadow. Therefore predictive maps have been used to find restoration sites (Greve et al., 2005). There are many potential causes for absence (outside of environmental conditions) including: Oxygen in sediment, lack of stabilisation of sediment by algae, and propagule absence. Despite this having the right environmental conditions indicates that a site may be appropriate for replanting and restoration. This study has identified suitable areas based on sediment type, wave exposure, tidal currents and depth that may be suitable for planting/restoration projects. Sites that are most suitable for restoration have been identified as having the lowest exposure (REI) values, soft sediments, low tide/wave energy and under 5m in depth. The best sites for restoration according to these parameters include; Pwehelli, Trefor, west Abersoch and Saundersfoot.

**Conclusion**

This study represents the first time predictive mapping of *Z. marina* has been attempted in Wales. Outputs from the model largely agree with known meadows (including those that were not used to inform the model) and matched with areas that had historical records. However it is important to remember that the model has identified niches that *Z. marina* can survive in and not actual distribution (Grech, 2009). Modelling is an advantage compared to in situ mapping because it requires fewer resources and can be implemented at broader scales. It also accounts for the dynamic nature of seagrass (Grech and Coles, 2010).

In Wales there is limited use for this methodology on a fine (bay size) scale. This is because of inconstancies and poor resolution environmental data, however better data does not currently exist. The result of low resolution data is errors of commission. Analysis showed that the five environmental parameters accounted for around half of the known distribution within the study bays. The rest of the distribution is explained by factors outside the scope of the model (Lathrop et al., 2001). Outputs from modelling are therefore more useful when used at a larger scale.

With regards to planning and conservation this model is an extremely useful tool as it can enable managers to make decisions within a quantified framework. Utilising modelling is
important because seagrasses are in decline and to conserve them better knowledge is required about their distribution (Kelly et al., 2001). Predictive mapping represents a tool that can be used to create a directed sampling programme as was conducted in this study at Abersoch. It can also be used to identify future restoration sites (Valle et al., 2013). The flexibility of this modelling approach means that in the future additional variables can be added to enhance the predictive power (March et al., 2013). Future developments should include; wave modelling that utilises bathymetric data and flood plume modelling. Anthropogenic impacts around the coast could be quantified and included. Additionally if more sites are identified using the model they can be used to better inform it in the future thus refining the output. Species distribution modelling represents a step forward in understanding Z. marina distribution in Wales and therefore represents a way to conserve this important habitat for the future.

References


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