Identification of Marine Management Priority Areas using a GIS-based Multi-criteria Approach.

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Abstract

There is a global issue of balancing resource exploitation with environmental protection. In particular, the marine environment is subject to many anthropogenic pressures which are most severe in coastal zones. Authorities managing these pressures have limited time and resources, so it is essential that they have access to data and modelling tools which help them prioritise their efforts.

This study presents a spatial modelling approach which draws together a range of key criteria into a single framework to identify marine areas which should be prioritised for management and monitoring. The study area, Sussex coastal waters (southern UK), was assessed through quantification and modelling of relative environmental score and fishing pressure score. Environmental score was assessed by combining ecosystem services provision, habitat diversity and sensitivity, based on seabed habitat data. Fishing pressure was assessed by combining fishing benefits, impacts and effort for specific local fisheries. The marine priority assessment was compared to the location of Marine Protected Areas to understand the relationship with existing management measures.

High and very high priority classes covered just 5% of the study area, with the highest priority area between Selsey and Bognor Regis. These habitats were ones found to have high environmental score (rocky reefs and seaweed-dominated sediment) concurrent with high fishing pressure. This modelling approach suggests that these areas should be the focus of further research, monitoring and potentially management measures. There was no significant difference between the priority score inside the MPAs and those outside, however, the environmental score was significantly higher inside MPAs. These findings suggest current MPAs are protecting valuable and/or sensitive habitats and management within these sites may have resulted in less fishing pressure.

Each multi-criteria element of the study individually advances our understanding of the value of this marine environment and the importance of fisheries in Sussex coastal waters. Together, the multi-criteria approach strengthens the knowledge of processes and interactions, building a robust evidence base for management decision making. A framework has been developed which, with the use of different or additional datasets, could be applied to many scenarios supporting environmental managers worldwide.

Keywords

Coastal zone, fisheries management, GIS, multi-criteria modelling, priority modelling

1. Introduction

Oceans cover over seventy percent of the Earth's surface and they are all interconnected, transcending national boundaries. Changes in one area of the ocean will affect other areas. Those changes have consequences as oceans provide a wealth of services and resources (Zhang & Sun, 2018). They regulate the climate and provide food, raw materials, medicines and innumerable benefits (Rickels et al, 2016). Despite the scale and value of the marine environment, it is under threat from a range of anthropogenic impacts such as climate change, plastic litter, pollution and overfishing (Farrell & Nelson, 2013; Hoegh-Guldberg et al, 2007; Jackson et al, 2001; Polovina, 2005; Rabalais et al, 2001; Walther et al, 2002). Impacts do operate in isolation when causing detrimental consequences but also act synergistically to change the environment at an unprecedented rate (McLeod & Leslie, 2009).

Coastal environments are particularly vulnerable to negative environmental impacts (Singh et al, 2017). Intertidal and coastal areas (<50m deep) only constitute 11% of the ocean area, but support *circa* 90% of fisheries (UNEP, 2006). From a terrestrial perspective, coastal land which is less than 10m above sea level is 2% of the land area but supports 10% of the human population and two-thirds of cities with a population of more than 5 million (McGranahan et al, 2007). There is enormous pressure on the coastal environment from a range of sources and the impact of these pressures has serious consequences for these areas which are particularly productive and are socio-economically valuable.

Fortunately, there are a range of international and national policy drivers to ensure that the marine environment is managed sustainably (Qiu & Jones, 2013). How these policies are implemented and whether they are sufficient, is still to be determined but there is a key principle for management development; management should be evidence based (Hyder et al, 2015). This requires rigorous scientific assessments of the marine environment and the impacts of the pressures. However, this can be daunting in the face of complex systems undergoing rapid change and under multiple pressures (Cloern et al, 2016). Specific management solutions are varied, but there is an emphasis on taking a whole ecosystem approach (McLeod & Leslie, 2009), having a diversity of management bodies (Ostrom et al, 1999) and being adaptable to change (Aguilera et al, 2015).

One management solution employed in coastal and marine environments is Marine Protected Areas (MPAs). MPAs are seen as a key part of marine governance, protecting and promoting biodiversity, ecosystem services provision and diverse socio-economic benefits (Russi et al, 2016). MPAs are specific areas of the sea which are reserved to protect the natural or cultural features within the enclosed area (Kelleher & Kenchington, 1992). The level of protection can vary from no take zones (where all extractive activities are prohibited) to multi-use sites (where lower impact activities are permitted) (Jones, 2014).

Marine Spatial Planning (MSP) is a further method and is seen as a way of improving decision-making and delivering an ecosystem-based approach to the management of marine activities (Gubbay, 2004; Duarte de Paula Costa et al, 2018). It aims to reverse biodiversity loss and build resilient, healthy ecosystems through multidisciplinary research and cross-sector initiatives (Douvere, 2008; Gissi et al, 2018). All marine activities are considered and access to the marine environment is granted to those activities which provide the most benefits to society. (Campbell et al, 2014, Venegas-Li et al, 2017). It can reduce conflict between activities such as aggregate extraction, renewable energy, commercial shipping, recreational uses and fishing (Ehler & Douvere, 2009).

Fishing is typically the most prevalent pressure on coastal ecosystems worldwide, but it is an essential socio-economic activity which provides many benefits (Jackson et al, 2001). In the UK, fishing is a major source of income and employment for coastal communities, as well as being a significant part of their cultural heritage and identity (Natale et al, 2013). Therefore, ensuring that fisheries are managed sustainably is important for both environmental and socio-economic reasons (Teixeira et al, 2018). Successful management requires an understanding of the spatial and temporal distribution of fishing activities (Vanstaen & Silva, 2010). This is because fishing activities have different impacts on the environment when they interact with different habitats and when different fishing methods are used (Jennings & Kaiser, 1998; Kaiser et al, 2002). Alongside an understanding of the distribution of fishing activities, the mapping of seabed habitats is important for supporting and monitoring the sustainable management of fisheries (Kaiser et al, 2016).

Fisheries are often managed either on a basis of interaction with seabed habitats (spatial restrictions) or on the basis of single species (quota systems) (Cryer et al, 2016; Singh & Weninger, 2009). Fishing activity in the UK is regulated under a complex system of management. Currently, the main management policy is the Common Fisheries Policy (CFP) (European Council Regulation No. 1380/2013), although it is likely that this may not be the case post Brexit. Often these regulations consider only a single species in isolation and do not take into account wider ecosystem interactions.

In turn, the marine environment is often managed or assessed based on a single criterion such as biodiversity (Jaeger, 2000; Wilson et al, 2006), the provision of ecosystem services (Carpenter et al, 2009; MEA, 2005) or sensitivity of seabed habitats (Eno et al, 2013; Nilsson and Ziegler, 2007; Tillin & Tyler-Walters, 2014). These criteria are used to assess the marine environment and the risk of it being damaged but assessing the value of the environment is a complex process, as the environment itself is complex.

However difficult, assigning value to the marine environment can guide decision making on the use of marine resources (Remoundou et al, 2009) and provide evidence for the development of management strategies (Derous et al, 2007). Often this involves attributing anthropocentric monetised value to ecosystem services which can seem to imply exploitation but can in fact result in greater protection for the environment (Kareiva et al, 2011). The recognition that intact ecosystems provide many benefits to humans in terms of services such as the provision of food, climate regulation and cultural value, can support the protection of those ecosystems (Carpenter et al, 2009).

An important factor in the functioning and resilience of ecosystems is biodiversity (McLeod & Leslie, 2009) and there is often more diversity when the habitat is more heterogeneous and structurally complex (Alsterberg et al., 2017). However, those habitats that are structurally complex and those that are not naturally perturbed are more likely to be adversely affected by damaging activities (Kaiser et al, 2002). Therefore, assessing the sensitivity of habitats – their resistance to damage and the time it takes for them to recover – is another important criterion when assessing anthropogenic pressures on the environment (Eno et al, 2013).

Balancing resource exploitation with environmental protection is a global challenge (Nguyen et al, 2016) and managers have only limited resources. They have to prioritise their efforts to areas where there is highest risk of environmental damage and greatest rewards for conservation efforts (Wilson et al, 2006; Ban et al, 2013). Mapping the marine environment, and its pressures, to identify priority areas can support managers in targeting their efforts in a transparent and scientific manner (Ojaveer et al, 2015; Breen et al, 2012).

Due to the complex nature of the marine environment, focussing on a single aspect is not sufficient to successfully manage the ecosystem as a whole (McGowan et al, 2017). Multiple parameters should be assessed when the aim is long-term conservation to restore or maintain healthy functions and processes (McLeod &Leslie, 2009). Other studies have focussed on single parameters (Tillin & Tyler-Walters, 2013; Eno et al, 2013; Dafouz et al, 2018; Pitcher et al, 2017). This study presents a spatial modelling approach which draws together a range of key criteria into a single, easy to understand framework to identify marine areas which should be prioritised for management and monitoring.

The areas identified through this multi-criteria spatial modelling approach are areas which score highly for environmental parameters (based on a combination of ecosystem services provision, habitat diversity and sensitivity) and are areas subject to high fishing pressure (based on a combination of fishing benefits, impacts and effort). The aim of this study is to identify areas in need of careful monitoring and potential interventionist management measures. This study presents a methodological framework to support marine managers internationally, who have limited financial and temporal resources, and has the potential to maximise the efficiency and effectiveness of future marine management.

2. Methods

The inshore waters (0-6 nautical miles) off the coast of Sussex, southern England, were used as a case study to develop a multi-criteria spatial modelling framework (Figure 1). The Sussex coast is a temperate coast with typical pressures, including recreational activities, aggregate extraction, renewable energy and maintenance dredging but the largest pressure is commercial fishing. A variety of fishing methods are employed in this area across a diverse range of seabed habitats. There are approximately 300 commercial fishing vessels with their home ports in Sussex. The most common fishing activity is netting, where long rectangles of net are anchored to the seabed for a tidal cycle. The second most common activity is potting for lobster, crab, whelk or cuttlefish, followed by trawling (towed gear). Commercial angling (hook and line) and dredging also occur but less frequently.

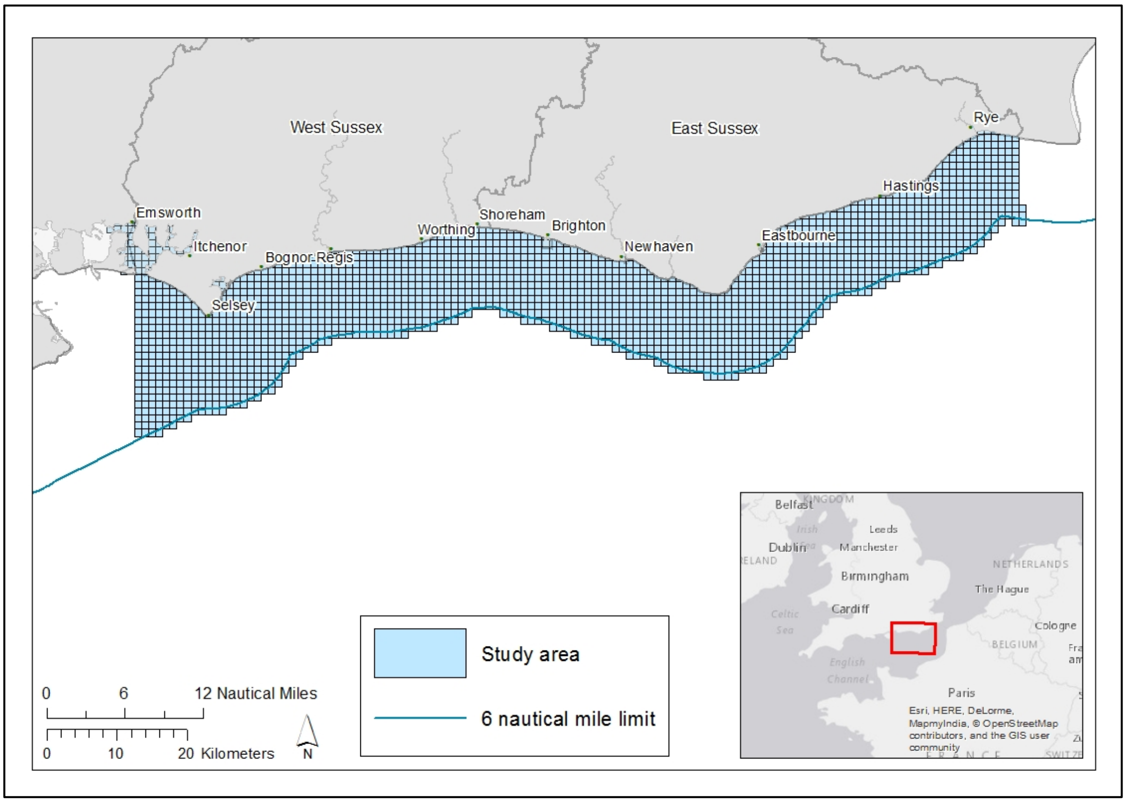

Figure 1: The study area; West and East Sussex coastal waters out to the 6 nautical mile limit and inclusive of the whole of Chichester Harbour, overlaid by a vector grid with 1987 cells 1km x 1km. Reprinted from Ordnance Survey (Digimap Licence) under a CC BY license, with permission from Crown Copyright and Database Right [2018], and ESRI (in full) basemaps.

The spatial modelling approach developed was used to highlight areas of the marine environment which could be prioritised for interventionist management. The inshore waters were mapped on a common grid with $1km^2$ cells. The use of $1km^2$ grid cells was considered to be a suitable compromise between the detail required for inshore management of fisheries and the marine environment, the interconnected dynamic nature of the environment, and the spatial resolution of the available data (Turner et al, 2015).

A priority score was derived from a combination of a calculated environmental score and fishing pressure score. The environmental score was based on seabed habitat data points assessed for their provision of ecosystem services, habitat diversity and sensitivity. The fishing pressure score was calculated by combining fishing benefits, impacts and effort. Further details on the scoring methodology are given below. The combination of the data layers resulted in a priority score for each cell on a scale of 1 very low to 5 very high. The parameters were selected for their relevance, applicability and availability. The parameters were selected for their relevance, applicability and availability. They are used here to demonstrate the framework, however, the modelling design means that other parameters could be used in future studies.

This can be summarised as:

$$Marine\ Priority\ Score = \sum_{i=0}^{n} Environmental\ Score\ x\ Fishing\ Pressure\ Score$$

Where:

Environmental Score = $\sum ecosystem\ services\ x\ habitat\ diversity\ x\ sensitivity$

Fishing Pressure Score = $\sum benefits\ x\ impacts\ x\ effort$

To test the functionality of the model, the resulting marine priority areas were compared against existing regulation employed in this inshore area; Marine Protected Areas (MPAs). These are the primary spatial management measures protecting sensitive habitats. It was hypothesised that the MPAs would have higher than average environmental scores, but would not be identified as management priority areas, as fishing pressure should be restricted in the MPAs. MPAs included Special Areas of Conservation (designated under the EU Habitats Directive 92/43/EEC), Special Protection Areas (designated under the EU Birds Directive 2009/147/EC) and Marine Conservation Zones (designated under the UK Marine and Coastal Access Act 2009).

2.1 Environmental score

The assessment of the environmental score was based on seabed habitats (n=177 at the most detailed level) classified using the European Nature Information System (EUNIS). Data points (n=2648) were available across the study area (from the Marine Recorder (JNCC, 2017) and Sussex IFCA survey data) at an average spacing of 240m, although they were significantly clustered (p value: <0.01, average nearest neighbour analysis).

As the environmental score was based on seabed habitat data points, it was assumed that there would be greater confidence in the accuracy of the habitat map, and therefore the environmental score, where there were more data points. To ascertain the confidence, point kernel density estimation was used to assess the density of the data points (Tomline & Burnside, 2015).

The environmental score was calculated by assessing the seabed habitat points for their ecosystem services provision, habitat diversity and sensitivity.

2.1.1 Ecosystem services provision

Twelve parameters were selected to represent the ecosystem services provision of the seabed habitats in the study area (after Galparsoro et al, 2014; Salomidi et al, 2012 and Fletcher et al, 2012). The data were selected due to the suitability of the spatial extent, habitat classification and description of service provision. The provision of each habitat (at a high, moderate, low or negligible level) was assessed for twelve ecosystem services: food, raw materials, climate regulation/air quality, natural hazard prevention, primary production, nutrient cycling, reproduction, biodiversity maintenance, water quality regulation, cognitive value, recreation and feel good (as defined by Salomidi et al (2012), based on the Millennium Ecosystem Assessment (2003)).

2.1.2 Habitat Diversity

Diversity of the seabed habitats was assessed by calculating the entropy value. Each seabed habitat data point was evaluated in relation to its neighbouring data points and an entropy value derived (de Smith et al, 2007). Minimum entropy occurred when all the neighbouring polygons were in the same class, indicating low diversity at the local habitat scale. Inversely, maximum entropy occurred when all the neighbouring polygons were in different classes, indicating high habitat diversity at the local habitat scale (Cushman & McGarigal, 2003; Jaeger, 2000; Vranken et al, 2015).

2.1.3 Sensitivity

Sensitivity of the key species present in each habitat was assessed based on information provided by the Marine Life Information Network (MarLIN) (2017), selected as an extensive and easily accessible source of information (Nilsson and Ziegler, 2007). For each habitat, sensitivity was assessed based on the resistance of the key species to abrasion and their time to recover from damage (Eno et al, 2013). Habitats were classed as low (key species had some resistance to damage resulting in little decline and could recover within 2 years), medium (species had some decline and took 2-10 years to recover) or high (species were easily damaged and took over 10 years to recover).

2.2 Fishing pressure

Most fishing activity in the study area was undertaken by small inshore vessels with one to three fishers on-board and on trips of less than 24 hours duration. Most vessels engaged in several different fishing methods throughout the year, sometimes concurrently. There were thirty-seven fisheries selected for analysis in this study; the combination of five fishing methods and twenty-five species.

Mapping of fishing pressure was based on observations of fishing activity (n=2364) made by Sussex Inshore Fisheries and Conservation Authority (IFCA) officers. Fishing vessels were observed across the study area with an average spacing of 425m but with significant clustering (p value: <0.01, average nearest neighbour analysis). Where no fishing vessels were observed, it cannot be assumed that no fishing took place, only that the activity was not observed. Despite this limitation, this dataset was the best available at the time of the study and the annual average effort 2012-2016 was considered to be suitable for the assessment of relative fishing effort (Vanstaen & Silva, 2010).

To assess the confidence in this data, kernel density was used to assess the density of the data points (Tomline & Burnside, 2015). In addition, the annual average patrol effort (km^2 of the sea patrolled) was calculated. This highlighted areas where there was greatest confidence that the observed fishing effort was representative of the true effort.

The assessment of fishing pressure was modelled using three parameters; 1) social and economic benefits 2) environmental impacts and 3) effort.

2.2.1 Benefits

The economic benefits of the selected fisheries were assessed under three criteria: value per tonne (first sale value), final economic output (value per tonne combined with a multiplier to assess contribution to UK's economic output), gross profit (seafood value minus running costs). The social benefits were also assessed under three criteria: port dependency (reliance of the local community on a particular fishery), employment (number of full time equivalent (FTE) jobs) and wage (average wage per FTE). Data was used from Seafish (2007), STECF (2016) and MMO landings data (2012-2016). The scores for each criterion were averaged to calculate the overall score for each fishery (MRAG, 2014; NEF, 2011; Williams and Carpenter, 2015; Williams and Carpenter, 2016). The score for each fishery was then averaged to calculate the score for each of five main fishing methods; angling, dredging, netting, potting and trawling, to allow for combination with the fishing effort.

2.2.2 Impacts

The environmental impacts of the selected fisheries were assessed under three criteria: fuel use (quantity), ecosystem damage and bycatch (using data from Seafish RASS (no date) and STECF (2016)). In the same manner as the benefits, the impact scores were averaged to calculate the score for each of the five main fishing methods.

2.2.3 Effort

Fishing effort was calculated as the annual average (2012-2016) number of fishing vessels observed per kilometre squared of the sea patrolled by Sussex IFCA's fisheries patrol vessel (FPV) *Watchful*.

When the FPV was at sea on routine patrols, the fisheries officers recorded the location and activity of observed fishing vessels. The maximum distance at which a fishing vessel could be identified was 2km, under average conditions, and this was used as a buffer around the vessel track, as recorded by the navigation equipment. The buffered track was intersected with a $1km^2$ grid to calculate the patrol effort; the area of sea patrolled.

The fishing vessel observations were also intersected with the $1km^2$ grid, for each of five fishing methods; angling, dredging, netting, potting and trawling. The number of observations was divided by the patrol effort to calculate fishing effort, eliminating any bias caused by some areas being patrolled more than others (Nelson, 2017; Strong & Nelson, 2016; Turner et al, 2015; Vanstaen & Silva, 2010).

3. Results

Individual outputs were created for each modelling parameter (ecosystem services, habitat diversity, sensitivity, benefits, impacts, and effort) and then combined respectively to form the core scores of environmental score and fishing pressure score (Table 1). These resultant layers were then mapped using a common Sussex inshore waters grid with $1km^2$ cells.

Spatial modelling criterion	Mean cell value	Co. Var. cell value	Minimum cell value	Maximum cell value
Ecosystem services	2.8	0.26	2	4.8
Habitat diversity	2.94	0.33	0	4.98
Sensitivity	2.3	0.33	1	4
Σ Environmental score	2.68	0.24	1.08	4.49
Benefits	2.45	0.11	2.17	2.87
Impacts	2.75	0.37	1.76	3.98
Effort	0.03	1.33	0	0.62
Σ Fishing pressure (all cells)	0.21	1.71	0	5
Σ Fishing pressure (obs activity only)	0.45	0.91	0.03	5

Σ Marine Priority Score (all cells)	0.18	1.89	0	4.99
Σ Marine Priority Score (obs activity only)	0.38	1.05	0.04	4.99

Table 1: Summary of the $1km^2$ Marine Priority Scores and individual scores for each criterion. Mean parameter $1km^2$ cell values shown; with coefficient of variation, maximum and minimum $1km^2$ cell value.

3.1 Environmental score

When the environmental scores were mapped on to the grid, the highest environmental scores were in the south west of the study area. There were no cells which were in the very low class and 30% of the cells (597) were in the high or very high classes (Figure 2).

This was based on a combination of ecosystem services provision, habitat diversity and sensitivity.

None of the habitats provided all twelve of the ecosystem services at a high level, but high energy infralittoral rock (rock with algae) provided eleven of the services at a high level and one at a moderate level. Subtidal sediments provided the least services. There were no cells in the very low class and 30% (590) of the cells were in the high or very high classes. The highest scores were in the west of the study area.

Over half (54%, 1073) of the cells had high or very high habitat diversity and these were located throughout the study area. There were 177 habitats recorded at the most detailed EUNIS level. This, coupled with the high entropy scores, demonstrated how diverse and complex the seabed was in this coastal area.

Generally, the habitats had low to moderate sensitivity (after MarLIN, 2017). They were vulnerable to damage but were able to recover in 2-10 years. When the scores for individual habitats were transferred to the grid, no cell was in the very high class but 15% of cells (302) were in the high class. This meant that physical damage would cause some decline in key species and it would take up to 10 years to recover. There were areas of high sensitivity across the study area but mainly in the west.

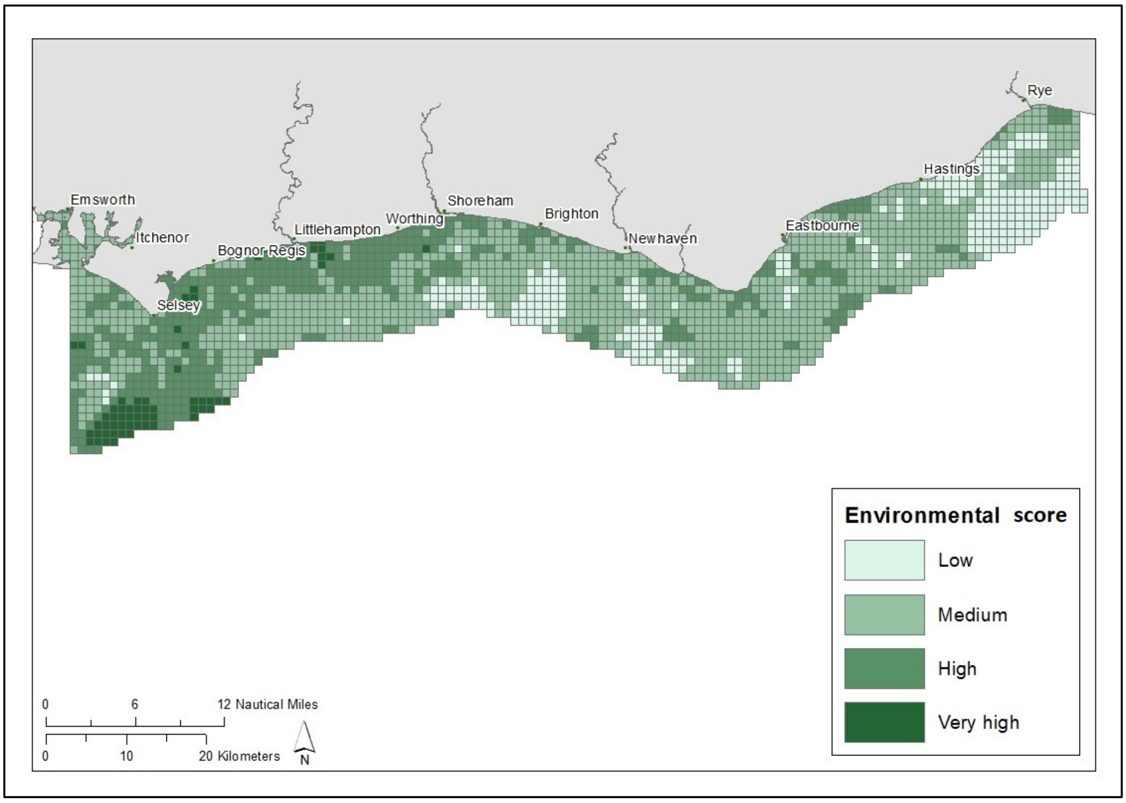

Figure 2: The environmental score across the study area based on the combination of the ecosystem services provision, habitat diversity and sensitivity scores. Data was classified into four environmental score classes using an equal intervals classification method. No cells were classified in the 'very low' class.

3.2 Fishing pressure

When the fishing pressure variable was calculated and mapped on to the grid, only 8% of the cells (163) were in the high and very high classes, mostly between Selsey and Bognor Regis (Figure 3). This parameter was calculated by combining fishing benefits, impacts and effort. This facilitated the mapping of, not only where the activities were taking place, but also the intensity; and accounted the different impacts associated with different fishing methods.

Angling and potting were the methods with the most economic benefits (value per tonne, final economic output and gross profit) and dredging the least. However, dredging provided the most social benefits (port dependency, employment and wage) and netting the least.

Under the environmental criteria, netting had the least impacts and trawling had the most. Netting had the most desirable score for the fuel use criterion and the ecosystem damage criterion, for most target species. Angling had the most desirable score for the bycatch criterion.

Overall, fishing effort occurred in 47% of the study area (936 cells) and the maximum effort was 0.62 vessels per km^2 for all methods summed. Trawling was the method with the highest annual average fishing effort (0.45 vessels per km^2) and dredging the lowest (0.08 vessels per km^2). Dredging also occurred in the least number of cells (12), whereas netting occurred in the most (554), followed by potting (438).

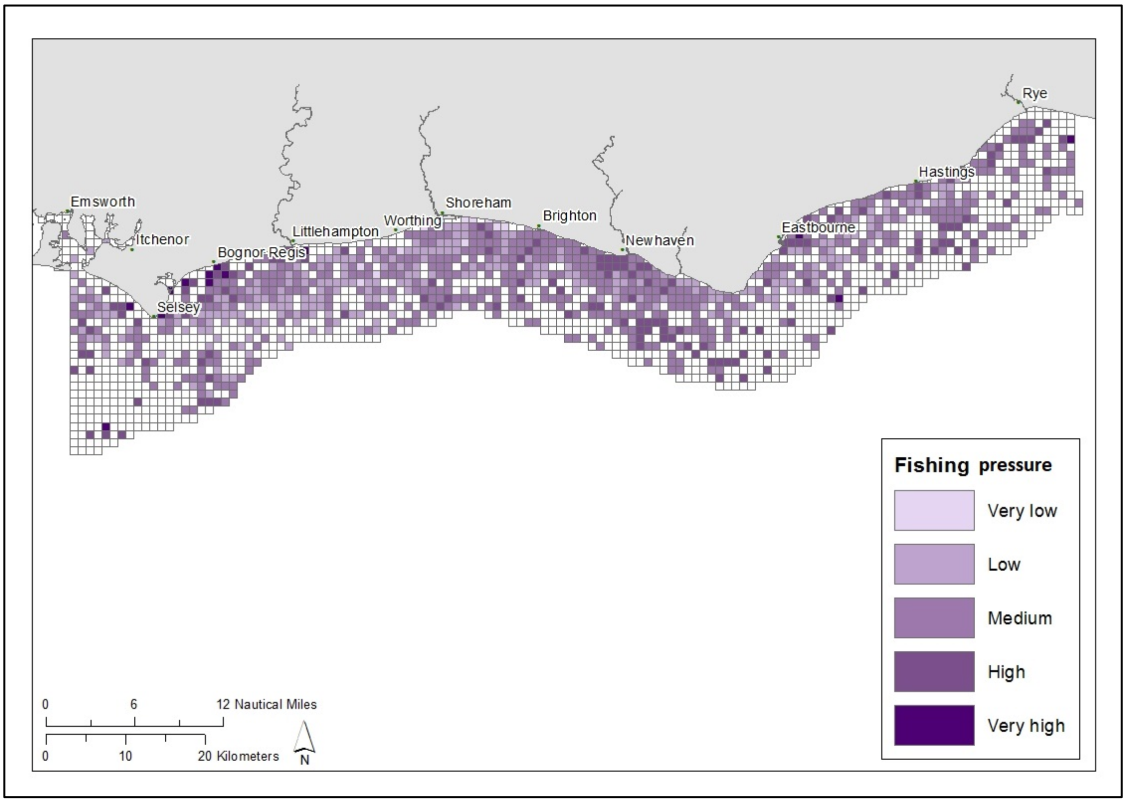

Figure 3: The fishing pressure across the study area, all fisheries combined, based on the combination of the impacts, benefits and effort. Data was classified into five fishing pressure classes using an equal intervals classification method.

3.3 Marine Priority Score

The final marine priority score was calculated by combining the environmental score and fishing pressure score. The result output showed that just 5% of the cells (101) were in the high and very high classes, mostly south of Selsey, between Selsey and Bognor Regis and near Newhaven extending through the east of the study area (Figure 4). Only 0.6% of the cells (12) were in the very high class and the majority were near Selsey. This geographic focus highlighted key areas which scored highly for both environmental score and fishing pressure score. The resultant map clearly identified both high priority areas and areas of lower priority.

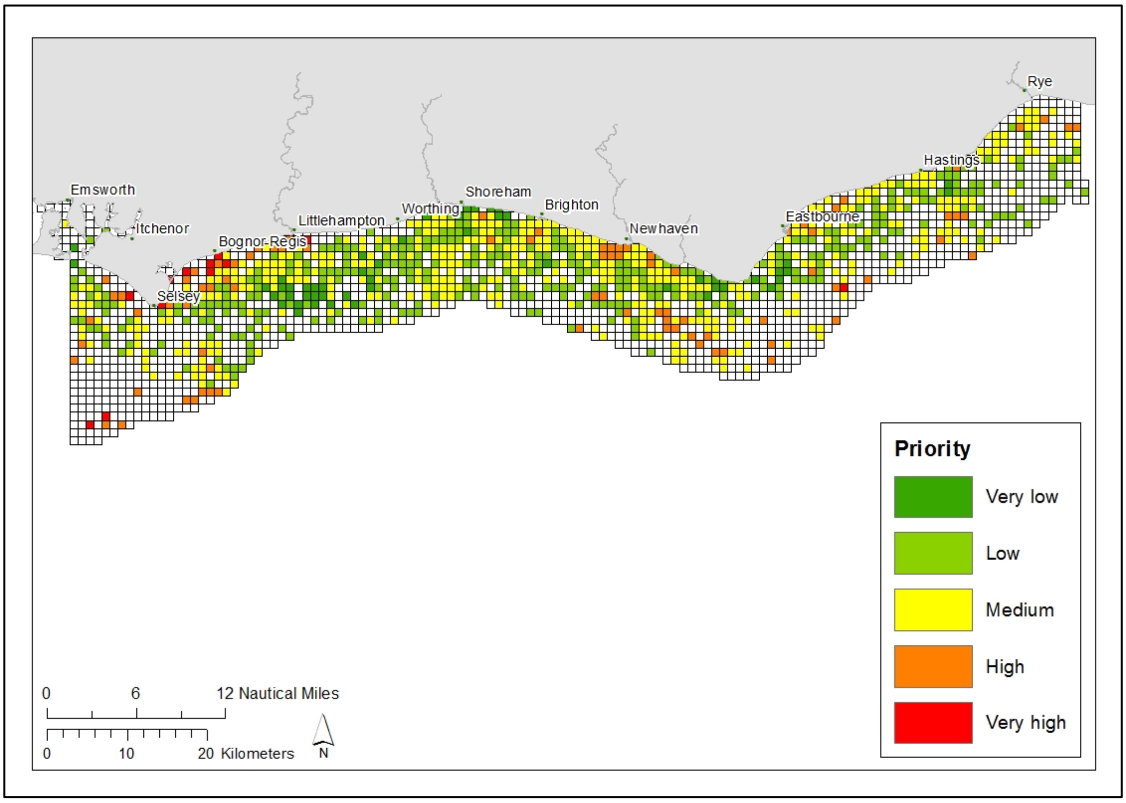

Figure 4: The management priority score across the study area, based on environmental score multiplied by fishing pressure. Five classes, equal interval. Score of 0 (white cells) = no observed fishing effort and therefore 0 priority. Score of 0.1 – 1.0 = very low, score of 1.1 – 2.0 = low, score of 2.1 – 3.0 = medium, score of 3.1 – 4.0 = high, score of 4.1 – 5.0 very high.

3.4 Marine Protection Areas

Only 4% (4.9km^2) of the Marine Protected Areas were classified as high or very high priority. There was no statistically significant difference in priority score inside the MPAs compared to outside (p value: 0.096). In contrast, 25% (31.8km^2) of MPA areas were classified as high or very high environmental score (Figure 5). The environmental score inside the MPAs was significantly higher compared to outside (p value: <0.01).

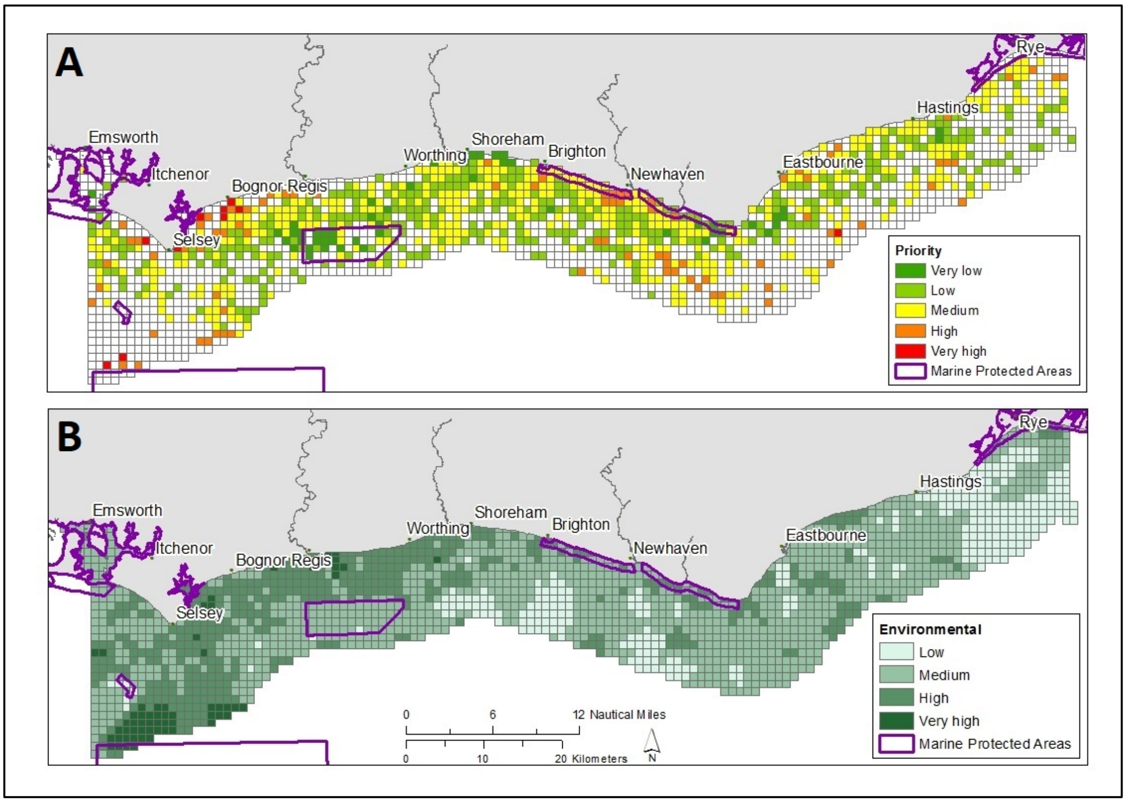

Figure 5: The interaction of Marine Protected Areas with A) the management priority score and B) the environmental score. Five classes, equal interval. Score of 0 (white cells) = no observed fishing effort and therefore 0 priority. Score of 0.1 – 1.0 = very low (no cells in the very low class for environmental score), score of 1.1 – 2.0 = low, score of 2.1 – 3.0 = medium, score of 3.1 – 4.0 = high, score of 4.1 – 5.0 very high. MPA boundary shapefiles publicly available, downloaded from www. data.gov.uk.

4. Discussion

This study has developed a spatial modelling framework for identifying priority areas in inshore waters to assist marine managers in focussing efforts and maximising effectiveness and efficiency. Multiple parameters have been brought together, reflecting the complex, multifaceted nature of the marine environment and the pressures exerted upon it. This approach has been applied to a case study site in the coastal waters of southern England, and contributes to the existing body of literature on the global issue of obtaining a balance between environmental protection, acknowledgment of the benefits from natural resources and supporting the livelihoods of local stakeholders. Fisheries were the focus of this study, assisting local management authorities in the development of a strong evidence base. With the use of different or additional datasets, this framework could be extended to other studies and variables, underpinning strategic decision making both nationally and internationally.

This study presents a methodological framework to identify priority areas where resources can be focussed, essential for effective conservation efforts (Johnston et al, 2015). These priority areas can then be the target for more in-depth research to identify any management needs (eg: spatial, temporal or gear-specific prohibition of fishing, voluntary measures or habitat restoration). For applied purposes, the model can be back-engineered to look in detail at each parameter. The modelling approach developed within this paper provides an open framework which would enable managers to identify and determine the key limiting factors in any areas highlighted to be of priority concern. A similar study highlighted areas which had high environmental value but low activity, as these areas were less impacted, had a better environmental condition and would need less action to improve or maintain than impacted areas (da Luz Fernandes et al, 2018). However, this was in contrast to the findings of the current study which highlighted areas of high activity in need of intervention, although with the tiered approach to the framework, this assessment could easily be conducted.

4.1 Summary of findings

The results of this study have revealed that high and very high priority classes occurred in just 5% of the study area, allowing managers to form a narrow geographic focus for their efforts. Having robust data to clearly highlight areas where limited resources should focus is crucial for effective conservation efforts (Johnston et al, 2015). The seabed habitat in the highest priority area was a mix of low lying rock and sediment, mostly dominated by seaweed. Rock with seaweed was one of the habitats which provided the most ecosystem services at the highest levels and rock or sediment with seaweed were some of the most sensitive habitats. This was also an area of high habitat diversity, resulting in high environmental score. Interestingly, this coincided with high fishing pressure where there was a relatively high level of netting and potting effort. This supports systematic conservation planning which can help to optimise conservation aims whilst acknowledging the challenges of meeting the needs of marine users and cost efficiency (McIntosh et al, 2016).

When analysed in conjunction with existing marine conservation measures to test the functionality of the model, high and very high priority classes covered only 4% of the total MPA areas. Analysis showed that there was no significant difference in priority score inside the MPAs compared to outside (p: 0.096). This suggested that the management that is in place is reducing fishing effort to relatively low levels and therefore these areas are not a priority as assessed by this study. Conversely, high and very high environmental score classes covered a greater proportion of the MPAs (25%), compared to the final marine priority score, and the environmental score within the MPAs was significantly greater than outside (p: <0.01). This suggests that the seabed habitats within the MPAs were perceived to be more valuable and may serve to illustrate the effectiveness of the parameters included in this modelling approach to assess environmental score. Protection of valuable or vulnerable habitats is one of the main reasons for designating MPAs (Jones, 2014). Site selection and management decisions that use a combination of science and stakeholder input can lead to MPAs which meet conservation objectives and are supported by marine users (Ruiz-Frau et al, 2015; Cvitanovic et al, 2012).

4.2 Environmental score

Generally, environmental score was higher in the west of the study area. This was where there was a combination of relatively higher ecosystem services provision, habitat diversity and sensitivity. Naidoo et al (2008) found that areas that were protected for high biodiversity did not deliver more ecosystem services than other, less diverse areas. However, in terrestrial systems, increased spatial heterogeneity can increase biodiversity and increase provision of ecosystem services by the species present (Fahrig et al, 2011). Diversity is an important element for assessment as it contributes to a robust, healthy ecosystem, better able to cope with changes (McLeod & Leslie, 2009) and habitat diversity is necessary to conserve marine biological diversity (Gray, 1997). However, the relationship between ecosystem services can be a complex one, and management aimed at increasing one particular service can decrease another one (Bennett et al, 2009).

4.3 Fishing pressure

Fishing activity which interacts with the seabed, such as bottom towed gear, is the most widespread cause of disturbance to seabed habitats (Hiddink et al, 2017). Habitats have a range of sensitivities to fishing activities and understanding these interactions is important for informing environmental impact assessments, evidencing marine spatial plans and in supporting sustainable use of the marine environment (Hiddink et al, 2007). Bottom towed gear, such as trawls and dredges, are recognised as causing damage to seabed habitats (Rijnsdorp et al, 2018) whilst the damage caused by netting and potting is considered to be less (Baer et al, 2010). This is comparable with the findings of this study where netting had the most desirable score for the environmental impacts criteria and trawling had the least desirable score, followed by dredging.

However, under the social criteria, dredging had the most desirable score, followed by trawling. These methods provided the most number of full time jobs, the highest average wage and the highest port dependency. Under the economic criteria, potting and angling had the most desirable score, with dredging the least desirable. Combining a range of impacts and benefits criteria allowed for a balanced objective assessment of which fisheries were providing the best value to society, ensuring access to common resources can be allocated in an equitable manner (NEF, 2011; Williams and Carpenter, 2015; Williams and Carpenter, 2016).

Direct interaction with stakeholders was beyond the scope of this study, therefore full understanding of the benefits of fishing to local communities was limited. If management measures were to be implemented, (for example, prohibition of towed gear over sensitive habitats) then extensive supporting evidence, assessment of the implications and consultation with stakeholders would take place. The mapping of coastal uses by a range of stakeholders can be beneficial in developing conflict scores which highlight areas in which there is the potential of conflicting uses (Moore et al, 2017; Tuda et al, 2014). This is in some ways similar to the priority mapping of this study in that there is the potential of conflict between the protection of specific areas and the preference of fishers to continue fishing there. This would be an interesting additional facet to look at in more detail in future research.

Monitoring the relative effort of fishing activities through high resolution, up-to-date maps is essential for the management of those fishing activities (Enever et al, 2017). Using data for 2012-2016 in this study, revealed that fishing activity was observed across some 47% of the study area and that effort for each of the methods was generally aggregated. Other studies have found fishing effort to be aggregated (Eigaard et al, 2017; Turner et al, 2015) and this can lead to de facto refuge areas for some species (Shephard et al, 2012). It also means that some areas are heavily impacted. Parts of the seabed in European waters were impacted by trawls up to 8.5 times per year which can be detrimental when the time for seabed species to recover from damage is longer than the trawling frequency (Eigaard et al, 2017). Identifying priority areas to be protected is key to successful management which balances the short-term benefits of exploitation with the long-term benefits of protection (Johnston et al, 2015; McIntosh et al, 2016).

4.4 Data confidence

There was highest confidence in the fishing activity data inshore from Shoreham to Newhaven. This was expected as the fisheries patrol vessel's home berth was in Shoreham and the area around this port was most frequently patrolled. For the seabed habitat data, there was highest confidence in the areas of Utopia and Kingmere Marine Conservation Zones where there have been extensive surveys to verify protected features. The area to the south of the study area between Shoreham and Eastbourne and east of Hastings had the least dense habitat data points. This could be due the distance from shore and the lack of MPAs or features of interest such as wrecks which could be the focus of research and incentives for divers. These areas could be targeted for surveys in the future to improve confidence.

4.5 Limitations

The results of this marine spatial modelling method highlight the effectiveness of this multi-parameter approach to provide a clear and easily communicated management prioritisation tool. However, there are limitations to the method. Scores were assigned on the basis of relativity, specific only to the study area for the time scale assessed. This was a restriction of the data which was available and the limited scope of this study. However, given the specific nature and character of marine environments and priorities, the modelling framework still provided a useful approach and assessment method which could be implemented internationally.

An additional consideration is that fishing effort was based on observations of activity. Areas where there was no observed activity, did not necessarily mean that no fishing activity occurred there. When the final marine priority score was calculated, those cells where no fishing was observed resulted in a zero priority score. This meant that the fishing pressure layer was the main driver behind the mapping of the priority score. Cells which were in the very high class for fishing pressure were likely to be in the very high class for the priority score, more so than the cells in the very high environmental score class. This was appropriate for highlighting the areas in which the pressure requires further management. The areas in which there is high environmental score but low pressure, are at less risk of damage from activities which have been observed to be occurring (da Luz Fernandes et al, 2018). These areas may benefit from management at some stage to prevent damage but were considered lower priority in this study than those high value habitats over which high fishing pressure was observed.

4.6 Areas for future research

There are many areas for future development of these approaches following this study. Now the framework has been established, additional or different datasets could be added to the model. Further, high resolution mapping of seabed habitats would be key to increasing the spatial accuracy of the habitat map. Increased understanding and research around the ecosystem services provision, developing more accurate understanding of the provision of services by the habitats in the study area and their underlying natural processes would advance the modelling. Moreover, attributing monetary value to services could be used to integrate advanced cost-benefit analyses (Kareiva et al, 2011).

Greater understanding of the role of diversity in marine ecosystems at various scales (e.g. habitat, species, genetic) would advance modelling. Furthermore, species abundance data could be integrated into the model. Sensitivity could be assessed for the impacts of various fishing gears, linking the distribution of fishing effort to specific habitats. Depending on data availability, additional elements could be added to the assessment of environmental score, such as essential fish habitat, spawning and nursery areas (Levin & Stunz, 2005).

For fishing, there could be further analysis of the impacts and benefits to ensure that the fisheries that are low impact and provide the most benefits to coastal communities are being supported and encouraged. It would be useful to assess other activities, such as wind farm development, aggregate extraction and recreational activities, to take a multi-sectoral whole ecosystem approach, ensuring all activities are managed in an equitable manner that minimises environmental damage. There is good spatial data available for some of these activities – renewable energy, aggregate extraction – but less data available for other activities such as recreational anchoring. This is the case for the study area and is also likely to be so for other potential study areas. The inclusion of additional criteria will depend on the available datasets and needs careful consideration to ensure that the modelled outputs are meaningful. Too many criteria could end up with a lack of clarity ie: everything averaged out to a medium level of priority.

Whilst there are recognised limitations and much additional work that would be beneficial to include, this study has achieved its aim and successfully presents a modelling framework for advanced identification of marine priority areas.

5. Conclusion

The marine environment is complex and dynamic. Therefore, multiple criteria should be considered when assessing management priorities and approaches for this ecosystem. This study proposes an uncomplicated, yet highly effective, method for practical marine management prioritisation. Fishing was selected as an example of a pressure on the coastal environment, as it is pervasive and has high socio-economic importance. Similar to the environment with which fishing interacts, the very nature of the activity is complex and well-suited to multi-criteria assessment of pressure. The analysis presented in this paper successfully combines fishing pressure scores with environmental measures to highlight areas which should be priorities for marine managers. These areas present target regions for further research as there is a risk that these habitats could be physically damaged by, and may be slow to recover from, specific fishing activity. Each modelling factor included in the analysis was important in isolation and can be used in discussions with stakeholders, however, when integrated in a multi-criteria framework they provided a clear indication of relative priority. Using the modelling framework developed in this study, other datasets can be added or substituted, providing a useful marine prioritisation tool for management authorities and conservation organisations worldwide.

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