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The emergence of a new marine renewable energy industry – what are the implications for fisheries?

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ABSTRACT

In the light of increasing global energy demands and the need to reduce greenhouse gas emissions, attention has recently turned to the sea as a large and renewable source of kinetic energy. Developments for wave and tidal energy extraction currently exist more in potential than in actuality, but there is huge impetus from political, environmental and commercial interest groups for rapid growth of the marine renewable energy sector over the immediate future. Such growth will inevitably have repercussions for other stakeholders in the marine environment. Concerns from fishery interests are likely to centre on access to fishing grounds and on changes to the physical structure and ecological functioning of fish habitats. We examine the extent to which fishery and marine energy resources overlap in UK waters. We also consider in more general terms how marine spatial planning decisions may affect fishery yield and the spawning potential of target stocks. Results of these analyses point to the conclusion that the greatest potential for interaction between the marine energy and fishery sectors is at a local scale in inshore environments. The potential near-field and far-field environmental effects of energy conversion devices, and their repercussions for marine productivity are as yet poorly understood. Marine spatial planning decisions need to be informed by both ecological and socio-economic considerations.

KEYWORDS: marine renewable energy, wave energy, tidal energy, fisheries, spatial interactions

INTRODUCTION

Fisheries are arguably the longest standing users of the marine environment, but in the modern world they must exist alongside an increasing variety of other activities that rely upon sea areas for space or resources. The emergence of a new ‘wet’ marine renewables industry, targeting resources of kinetic energy in waves and tides (Pelc & Fujita, 2002) is perhaps the most recent such activity. Given the rapid development of this sector, and the high potential seen by government, developers and investors, there is an urgent need to understand how marine energy extraction might interact with fisheries.

Marine spatial planning guidelines in relation to marine energy developments are already being drawn up (e.g. Marine Scotland, 2010; Guernsey Renewable Energy Commission, 2010). These are largely based on available information on the distribution of marine fish and fisheries (among other activities), on information related to offshore wind energy developments (e.g. Gill & Kimber, 2005) and on information on the general ecology of species that occur in potential development areas. Reviews have considered various issues such as collision risk (Wilson *et al.*, 2007), marine energy converters as artificial reefs or fish aggregation devices, biofouling and sedimentation, underwater noise and electromagnetic fields and development areas as no-take zones (Langhamer *et al.*, 2010). Work on wave energy converters in Swedish waters also highlights the potential value of developments in terms of creating new ecological space (Langhamer & Wilhelmsson, 2009; Langhamer *et al.*, 2009).

In this paper we address two main aspects of the potential interactions between marine renewable energy developments and fisheries. Firstly, we consider the extent to which there is potential for spatial overlaps between two sectors. Intersections between the two types of activity, and the resources on which they depend, dictate the potential for direct and indirect interactions (Figure 1). Secondly, we use a simple spatial fishery model to consider whether exclusion of fishing mortality from development areas has the capacity to deliver long-term benefits for the sustainability of fishing. Compulsory exclusion zones have yet to be defined in relation to wave and tidal energy development, but for safety and operational reasons it is likely that they would function as *de facto* exclusion zones even in the absence of legislation. Based on these analyses we draw some general conclusions about the likelihood of interactions between the wet renewables and fisheries sector, and on the possible consequences of these for fisheries.

MATERIALS AND METHODS

Data sources

Data on UK fishery landing weights and values for landings by UK vessels into the UK and abroad were obtained from the Fisheries Statistics Unit of the Marine Management Organisation. Data for a range of demersal, pelagic and shellfish species were requested for the ten year period 2000-2009, specific to ICES rectangles in ICES sub-areas IVa-c, Vb, VIIa-k and VIIIa, covering the majority of landings by UK vessels[1]. Ten-year annual average landings weights and values were calculated for each species, or for groups of species, in each ICES rectangle. Average values were calculated after adjustment to 2009 equivalents using data on the Retail Price Index (RP02) from the UK Office for National Statistics (http://www.statistics.gov.uk/downloads/theme_economy/rp02.pdf).

International Bottom Trawl Survey (IBTS) data were obtained from ICES (http:/datras.ices.dk/Home/Descriptions.aspx). Data on catch per unit effort (CPUE) per

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[1] At the time or writing, fishery data available to the authors were not complete for all areas and species. Data were missing for IVc and total landings quantities and values were not available. The analyses in this paper are thus conditional on an incomplete data set.

length per haul from the NS-IBTS (North Sea) and ALT-IBTS (north-western areas) series were downloaded for all species for 2000-2009. Length-weight relationships from Coull *et al.* (1989) were used to calculate CPUE values in weight for selected species. Ten-year average CPUE values for each species were calculated for sub-rectangles of ICES rectangles, using data for all quarters of the year available for each survey. For the purposes of these analyses sub-rectangles were defined by dividing ICES rectangles into nine (3 × 3), each being 20′ longitude by 10′ latitude. A complete list of hauls was compiled by examining data for all species, and any species for which no data were given for a particular haul was assumed to have a zero catch.

Data on the wave and tidal energy resources in UK waters were obtained from the UK Department of Trade and Industry (DTI, 2004). Annual mean wave and tidal power data were used, summarised by sub-rectangles (20′ longitude by 10′ latitude) as for the IBTS data (Figure 2). Linear Interpolation was applied to wave power data for areas to the west of 12°W to give the required sub-rectangle resolution.

Analysis of the relationship between fisheries and energy resources

We first addressed the question of whether fishery landings are positively or negatively associated with areas of high wave or tidal power density. Given that any relationship with power density may well be non-linear, and that we are interested only in spatial correspondence and not in causation, we simply tabulated the frequencies of rectangles of high power density against frequencies of high landings. The threshold for ‘high’ landings or power density was taken to be the upper quartile of values. Fisher exact tests (Sokal & Rohlf, 1981) were used to measure the statistical significance of any association. Landings were standardized to sea area within each rectangle. Note that, since the tests were not sensitive to the exact method of standardization, landings per unit of sea area were used throughout, unlike the following analyses in which coastline lengths were used for coastal species.

Second, we attempted to measure the extent to which wave and tidal energy resources overlap with different fisheries. This analysis proceeded on the basis of three main assumptions: (i) that all energy resources are available for extraction; (ii) that areas with the greatest power density are likely to be exploited first; and (iii) that the ten-year average of landings or value in an area provides an indicator of its fishery importance relative to other areas. We considered that the spatial resolution of fishery data (ICES rectangles - 1° of longitude by 30′ of latitude) was too coarse to represent adequately the scale at which energy resources are likely to be targeted, so we pro-rated landings across sub-rectangles within ICES rectangles. For open water species (all fish species, shellfish such as queen scallops and *Nephrops*) we distributed the landings or values among sub-rectangles according to their sea areas. For coastal species (mussels, cockles) we distributed landings or values according to the length of coast in each sub-rectangle. For predominantly coastal species (lobsters, green crab) we distributed landings according to the second method if an ICES rectangle contained any coastline and otherwise according to the first method. Sea areas and coast lengths were estimated on the basis of pixel counting for a high resolution bitmap picture of UK and European sea areas. Total available power in each sub-rectangle was calculated by multiplying average power density by sea area.

The data set for analysis consisted of spatially matched pairs of power and landings values for sub-rectangles. For each comparison, the data were sorted in descending order of power density (N.B. power density rather than total power), then cumulative totals were calculated for both total power and landings and expressed as cumulative percentages for the purposes of graphical display. Plots of cumulative landings (*y*-axis) against cumulative power (*x*-axis) illustrate the relative distribution of the fishery and energy resources (Figure 3): a straight line (1:1) relationship indicates that the two resources are distributed identically; points above the line indicate that the fishery is aggregated with respect to the energy resource; points below the line indicate that the fishery is dispersed with respect to the energy resource.

Averages over ten years are assumed to provide a good representation of the importance of a given location for different fishery outcomes. However, such averages possibly under-represent the *potential* fishery importance of a given area. For this reason, we repeated the overlap analyses using instead the ten-year maximum landings from each ICES rectangle. However, results of these analyses are not presented because they showed very similar patterns to those based on mean landings. It appears that, in relative terms, mean landings give an adequate representation of the spatial variation in fishery productivity. Future analyses could be based on maximum landings per rectangle if we were interested in the potential for marine energy resources to overlap with *absolute* values for the maximal fishery productivity harvested from any given area.

The assumption that availability of the energy resource depends only on the density of that resource at a given location is highly unrealistic. Given that, for reasons of grid availability, ease of installation, maintenance costs and many other factors, most developments are likely to be in inshore environments, we repeated all of the analyses above with data restricted to being within 12 miles of the coast, i.e. effectively the UK Territorial Sea.

Analysis of the relationship between fishery resources and marine energy

The analyses above consider the extent to which the outcomes of fishing activities, i.e. landings quantities and value, show spatial correspondences with the resources of wave and tidal energy available for extraction. Next, we examine the relationship with marine energy of the resource on which the fishery outcomes depend, i.e. fish. For a small selection of demersal species likely to be sampled adequately by the survey gear, we examined the ten-year average CPUEs (in weight) for IBTS catches summarised by sub-rectangle.

If marine energy is a factor defining the ecological niche of a species, there is likely to be an optimum energy value above or below which (other factors being equal) abundance would be expected to decline. This type of relationship, where species abundance is conceptualised as having a unimodal rather than linear response to environmental gradients, underlies the correspondence analysis family of methods (e.g. ter Braak, 1985). We used Canonical Correspondence Analysis (CCA) to analyse the survey data, with gradients of species composition explicitly constrained to be a function of wave and tidal power density (ter Braak, 1986). Two analyses were conducted: (i) an unconditional analysis was performed, with no account taken of sub-rectangle location; and (ii) a 'partial' analysis (pCCA) was performed, in which the effects on species abundance of location (latitude, longitude and distance to coast) were taken into account before extracting gradients in relation to marine energy. The analyses were first undertaken using all available data, then repeated for sub-rectangles within 12 miles of the coast. These analyses were undertaken using the 'cca' function of the 'vegan' package of the R statistical environment (Oksanen *et al.*, 2010). Note that ALT-IBTS and NS-IBTS data were treated without distinction in the analyses, but given the difference in geographical coverage of the two surveys the conditioning variables (latitude, longitude and distance to coast) will effectively absorb any survey differences in the pCCA.

Spatial fishery models

One of the most obvious potential impacts of marine renewable energy developments on fisheries is that they occupy space. We used a per recruit modelling approach to consider the implications for fishery yield and the spawning potential of exploited stocks of excluding fishing from parts of the overall stock area. Appendix I gives details of this model which is a generalisation in matrix form of an approach to spatial fishery modelling developed by Side & Jowitt (2005). The model describes fish movements between areas open and closed to a fishery in the context of age-based population dynamics.

Bell & Side (in prep.) have used Monte Carlo simulations to show the relationship between movement patterns and exchange rates between areas of differing size, shape and configuration. They parameterised movement rates in terms of σ, the standard deviation of a bivariate Normal distribution describing the destination points of random walk movements. Based on Bell & Side's results, we adopted a value of σ equivalent to an annual emigration rate of 10% from an exclusion zone covering 20% of the area occupied by a stock. This calibrated value of σ then allowed us to estimate equivalent exchange rates for other sizes of exclusion zone. The implications of larger and smaller values of σ (high and low movement rates) were also explored. Per recruit modelling proceeded with parameters equivalent to (in the absence of spatial management) an annual fishing mortality of F=0.1 at a fishing effort of 100, natural mortality of M=0.1, growth specified by von Bertalanffy parameters K=0.1 and L_∞=100 and an exponent for the length-weight relationship of 3. Model outcomes were collected in terms of yield (removed catch weight) per recruit and spawning stock biomass (SSB) per recruit.

RESULTS AND DISCUSSION

Overlap of marine energy resources with fisheries

Considering all sea areas, the spatial distribution of landings for most of the species considered show statistically significant associations with the locations of highest wave and tidal power density (Table 1). Pelagic species and some demersal species are positively associated with areas of high wave power density and tend to be negatively associated with areas of high tidal power density. Conversely, most shellfish species and flatfish species are negatively associated with high wave power density and tend to be positively associated with high tidal power density. In many cases these associations are largely trivial, inshore-offshore distribution patterns. For example, blue whiting are predominantly taken in offshore north-western areas, where wave power densities are high. Conversely, cockles and mussels are obviously coastal fishery resources, and tidal energy resources tend to be concentrated close to coasts. If the analysis is restricted to waters within 12 miles of the coast then the number of statistically significant associations is much reduced (Table 2). No species shows a statistically significant positive association with tidal power density but two pelagic fish species (herring and mackerel) still show a positive association with wave energy density. *Nephrops* shows negative associations with both wave and tidal energy density, which is perhaps unsurprising given the requirements of the species for mud substrates which depend for their existence on a low energy (depositional) environment.

Wave and, particularly, tidal energy resources are not distributed homogeneously through the marine environment (Figure 2). For tidal energy, 90% of the resource is located within 26% of the sea area for which there are data, and for wave energy 90% of the resource is located with 70% of the sea area (Figure 4). Within 12 miles, the corresponding figures are 32% and 67% of the sea area for tidal and wave energy respectively. Given these non-homogeneous distributions, it is clear that strong overlaps with fisheries could only occur if landings were strongly aggregated within energy-rich areas. For most species, taking the whole areas over which tidal and wave energy power data are available (Figure 2), landings are not strongly aggregated within areas rich in either tidal energy (Figure 5) or wave energy (Figure 6). Pelagic fish species, particularly mackerel and blue whiting, are landed predominantly in areas of least tidal power density (i.e. the least likely areas to be exploited, on the upper ends of the *x*-axes in the cumulative plots - c.f. results in Table 1), which is to be expected given the lower levels of tidal power density offshore. The same is true of most of the demersal fish species, although sole and whiting have appreciable proportions of their total landings from areas of intermediate tidal power density. Landings of shellfish species show a diversity of distributions in relation to tidal power density. Squid and *Nephrops* landings are concentrated in areas of low tidal power density, other species such as queen scallops and lobsters are taken also in areas of intermediate power and green crab landings are the most associated with areas of high power density. Corresponding data for wave power show some different overall patterns (Figure 6), but it would be similarly concluded that the most energy-rich areas are not the areas of greatest importance in terms of fishery landings. Disproportionate landings of, especially, blue whiting are taken at some intermediate wave power densities, but even in this case more than 40% of the wave resource would need to be exploited before the spatial overlap would approach proportionality with landings.

As noted above, for operational and economic reasons it is not fair to assume that power density is the only factor determining the attractiveness of a given location for commercial extraction of energy. In particular, developments are much more likely in inshore waters. Restricting the analysis to waters within 12 miles of the coast does not change the pattern appreciably in relation to tidal power density (Figure 7): individual species show some different curves, but it is still only green crab for which the landings are disproportionately associated with areas of highest tidal power density. This reflects the fact that the areas richest in tidal energy are situated in inshore waters (Figure 2). For wave power, however, the patterns change dramatically in inshore waters (Figure 8). Pelagic fish landings are the most strongly associated with areas of high wave power density. This is particularly true of blue whiting and to a lesser extent mackerel. Landings of demersal fish are more closely associated with high wave power densities within 12 miles than overall, but 20% of the wave resource could be exploited before there were proportionate effects on the most closely associated species (saithe and ling). Landings of shellfish species appear least likely to intersect with wave energy extraction. Of all shellfish species, brown crab shows the steepest ascending curve of cumulative landings over the range of highest wave power densities, but even in this case the overlaps do not approach 1:1 proportionality.

Figure 9 shows the percentages of landings of each species that occur in sub-rectangles with the highest tidal or wave power densities amounting to 10% of the total power resource available within the area concerned. It can be seen that if this amount of tidal energy was extracted from these sub-rectangles it would intersect with less than 10% of the landings of any species, either over the whole spatial domain covered by the data or within 12 miles of the coast. Green crab landings show the biggest overlap, particularly over the larger spatial domain (7%). Monkfish inside 12 miles has the next biggest overlap (3%). In terms of the wave power, the spatial overlaps are small for landings of most species except for mackerel (12%) and blue whiting (76%) inside 12 miles. Aside from these two pelagic fish species, the largest overlap of the wave energy resource is with ling landings (3%).

Repeating the cumulative curve analyses with landings values for species groups shows a similar picture to the analyses with landings weights: the most energy-rich areas locations do not strongly overlap with the locations supporting the greatest landings values (Figure 10, Table 2). The greatest overlaps occur with landings value of pelagic species inside 12 miles.

Although the overlaps, and hence the potential for interaction between marine energy extraction and fisheries appears to be small at a UK scale, this is not to say that this is necessarily true at a regional or local scale. For example, the top 10% of wave power available inside 12 miles is concentrated to the west of the Western Isles of Scotland. The landings of ling, comprising 3% of the UK total inside 12 miles, or brown crab, comprising 1.4% of the UK total inside 12 miles (Figure 9), may be of considerable importance in this region, still more so the 1.7% of total UK landings value (across the species considered) inside 12 miles. Conversely, these analyses may overplay the importance of overlaps for some species. Notably, 76% of blue whiting landings inside 12 miles overlap with 10% of the wave energy resource (Figure 9), but this should be interpreted in the light of the fact that only 0.2% of landings of this species are taken inside 12 miles. Full regional analyses, beyond the scope of time and space available for the present paper, should be a priority for the future.

Finally, as a point of interpretation, it is worth pointing out that spatial overlaps of marine energy resources with fisheries provide only an indication of the potential for interactions to occur between energy extraction and fisheries. They do not imply that interactions necessarily will occur, still less that any interactions will be conflicts. Moreover, examination of data at a smaller spatial scale than is currently possible would be needed to determine whether commercial fishery harvests and marine renewable energy developments are likely to occur at the same locations.

Demersal fish distribution in relation to wave and tidal power density

Canonical Correspondence Analysis (CCA) indicates that marine energy accounts for only small amounts of the variation in demersal fish species composition. For the analyses including both inshore and offshore areas, wave and tidal power density accounted for 12.6% of the unconditioned variance. For the pCCA, in which the CPUE data were first conditioned on geographical location (latitude, longitude and distance from the coast), the power variables accounted for only 1.7% of the variance. Corresponding figures for the analysis including only inshore areas (inside 12 miles) are 17.8% and 1.8% of the variance for the unconditioned (CCA) and conditioned (pCCA) analyses respectively.

All four analyses (CCA and pCCA for all data and for sub-rectangles within 12 miles) give generally similar results in terms of the relationships of the species with changes in power density (Figures 11 & 12) (note that although the pCCA biplot in the lower panel of Figure 12 appears at first sight to be very different from the corresponding CCA biplot, the spatial arrangements are in fact very similar if the plot is first rotated through 90° clockwise and then reflected about the CCA1 axis). The species scores in the biplots indicate the optimum locations of each species relative to the gradients in wave and tidal energy density, the directions and strengths of which are indicated by arrows extending out from the origin. Ling, saithe and, to a lesser extent, monkfish appear to be the species most associated with higher wave power densities. Cod is generally associated with higher tidal power densities. This is even more true of thornback ray, although after accounting for location in the pCCA, this species appears to have an equal association with high wave power density. Sole shows an even stronger relationship with high tidal power densities over the larger spatial domain, but inside 12 miles the relationship appears to be in the opposite direction, particularly after accounting for the effects of geographical location. Haddock, whiting and plaice generally appear to be associated with low densities of both wave and tidal power, although there is some suggestion of association with higher tidal power densities in whiting and plaice in the CCA for the larger spatial domain.

The conclusion from these analyses is that, although some associations of demersal fish species with marine energy conditions can be identified, these are generally weak and account for very little of the spatial variation in survey catch rates. Much of the ‘explanatory power’ of the energy variables is removed after factors of geographical location are accounted for in the analyses, suggesting that wave and tidal power density co-vary with other ecological factors and are not necessarily causal factors in their own right. Of course, in terms of any interactions with activities relating to the extraction of marine energy, it matters not at all whether fish occur at a given location because of its energy characteristics *per se*, or because of other features of their habitat that happen to co-vary with energy. However, it is reasonable to suppose that propensity to interact with energy extraction activities might be at least partially related to the importance of energy as an ecological factor.

This analysis serves to illustrate questions that can be addressed using existing survey data, specifically the relationship of fish distribution with hydrokinetic energy in the marine environment which is relevant to potential vulnerability of fish populations to energy extraction activities. We recognise that it is a very crude analysis of a limited set of survey data considered at a very aggregated level and including only a few species and a few possible factors that might explain their distribution. Many more rigorous analyses are possible, and in fact desirable given the need to predict the population level consequences for fish of renewable energy developments and other human activities in marine environments. Good data exist on recent and historical fish and benthic invertebrate distributions in north-west European waters, and extensive use has been made of such information to examine issues such as fishing disturbance (e.g. Callaway *et al.*, 2002) and responses to climate change (e.g. Perry *et al.*, 2005). Species geographical distributions can be modelled and predicted outside the domain of observed data using data as simple as incidence records (e.g. Phillips *et al.*, 2006). Such models, particularly where they consider ecological niche requirements in relation to factors relevant to marine energy extraction, could usefully contribute to spatial planning processes.

Spatial fishery modelling

The results of per recruit modelling with random fish movements at a rate equivalent to 10% annual emigration from a circular fishery exclusion zone of 20% of the total stock area are shown in Figure 13. Exclusion zones of increasing size result in increasing losses of yield per recruit (a proxy for fishery yield), except at very high levels of fishing effort that would, in the absence of spatial management, represent heavy growth overfishing. At these high levels of fishing effort, exclusion zones offer some protection of yield per recruit. Exclusion zones result in gains in SSB per recruit (a proxy for spawning potential) at all levels of fishing effort, the size of gain depending on size of exclusion zone.

The fishing mortality at which yield per recruit is maximised (F_{max}) and the fishing mortality at which SSB per recruit is at 35% of its unexploited level ($F_{35\%}$) are two biological reference points which are commonly used as a proxy for the fishing mortality at which long-term yield is maximised (F_{MSY}). Figure 14 shows some of the properties of these reference points calculated at different sizes of fishery exclusion zone. The fishing effort required to achieve these reference points increases with size of exclusion zone (Figure 14a). The exclusion zones carry costs in terms of foregone yield per recruit, but these are not proportional to loss of fishing area(Figure 14b). If fishing at maximum productivity (i.e. F_{max}), exclusion zones carry benefits in terms of gains in SSB per recruit, although again these are not proportional (Figure 14c).

The costs and benefits of exclusion zones depend not only on their size but also on the movement rates of the target stock, which define how individuals move into and out of closed areas, and also on how the total exclusion zone is distributed through the overall stock area. Figure 15 shows SSB per recruit curves for low, moderate and high movement rates of fish for 20% exclusion zones divided into different numbers of circular areas (from 1 to 1,000). For low movement rates (Figure 15a), there are benefits at any given level of fishing effort for any configuration of exclusion zone. The benefits decline as the exclusion zone is increasingly sub-divided, but even 1,000 tiny zones offer substantial gains in SSB per recruit. At moderate movement rates (Figure 15b) these gains are less, and become negligible if the exclusion zone is excessively sub-divided (100-1,000 circular areas), and at high movement rates (Figure 15c), there are virtually no benefits from any configuration of exclusion zone.

These results demonstrate that fishery exclusion zones, such as might be established around marine renewable energy developments, offer potential fishery management benefits in terms of protecting spawning potential and increasing resilience to growth overfishing. However, at realistic sizes of exclusion zone in relation to whole stock areas, these benefits are likely to be negligible except in the case of stocks with extremely low movement rates. It is well recognised that high movement rates are likely to negate the effects of fishery closed areas (e.g. Hilborn *et al.*, 2006). In the present context, we conclude that exclusion zones around arrays of wave and tidal energy extraction devices are unlikely to provide significant benefits for fisheries based on highly mobile fish stocks distributed at large spatial scales (i.e. the main demersal and pelagic fish stocks such as cod, haddock, herring and mackerel). Any benefits of exclusion zones around marine energy developments are likely to apply to stocks that are sedentary, or which are mobile over small spatial scales, and which occur at small spatial scales. This is likely to apply particularly to small-scale shellfish stocks of local importance, such as lobsters and bivalve species, particularly (given the likely distribution of developments) those in close inshore waters. In such cases, the aggregate exclusion zone may be significant in local terms, even when distributed between a number of small areas.

Finally, it is worth adding that this consideration of the fishery implications of exclusion zones around marine renewable energy developments treats all areas as equal, ignoring the potential benefits that could accrue from provision of new ecological space. Reef effects, fish aggregation (and hence disproportionate protection given exclusion areas) and ecosystem services provided in protected habitats all have the potential to provide fishery benefits in terms of productivity, mortality and protection of spawning potential. Again, these are likely to be most relevant at small spatial scales, at a local level.

CONCLUSIONS

The most clear conclusion that emerges from these analyses is that interactions between extraction of marine energy and fisheries are most likely to occur close inshore at regional or local scales. The potential for spatial overlap between the sectors appears to be small at a national scale, but given the concentration of the greatest wave and, particularly, tidal energy resources at a few localities, notably the Northern and Western Isles of Scotland, it is possible for overlaps to be much more significant at local scales.

Clearly, it would be desirable to extend the current analyses to cover these local scales. It would certainly be possible to interrogate the currently available data at regional scales, but what is really needed for a robust and rigorous analysis is spatially-explicit data on catch and fishing effort at a fine spatial scale, and such data are rarely available. Vessel Monitoring System (VMS) data are available to map the activities of larger (>15 m) fishing vessels, but such information does not exist for smaller fishing vessels that are likely to be an important component of inshore fishing fleets (e.g. many small creel vessels fishing for lobsters). Log-book records are the most likely source of information in this respect, but instituting appropriate recording schemes and data handling protocols is neither trivial nor cheap.

The second main conclusion is that interactions, and in particular the capacity for fishery exclusion zones to influence yield and spawning potential of stocks in areas containing marine energy developments, are relevant mainly to species that are sedentary or of limited mobility at the spatial scale of developments. This is for two reasons: firstly, interactions have the greatest potential importance for stocks that extend over small spatial scales, i.e. areas of development occupancy cover a greater proportion of small stock areas; and secondly, mobile species are able to move freely between development areas (possible exclusion zones) and unaffected habitats. By this reasoning, fisheries for shellfish (e.g. lobsters) are most likely to interact with marine energy developments. Shellfish such as lobsters have already been the focus of small-scale experiments with closed area management around the UK (Hoskins, 2006), and work is currently underway examining the lobster populations around the European Marine Energy Centre's wave energy test site at Billia Croo in Orkney[2].

We have been careful to use the word 'interaction' rather than 'conflict' or 'impact' in this paper, since interactions are not inevitably negative. Indeed, the spatial fishery modelling

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[2] Work funded by Scottish Government, co-ordinated by EMEC and involving ICIT (Heriot-Watt University), Orkney Fishermen's Society, Orkney Sustainable Fisheries, Orkney Fisheries Association and Orkney Lobster Hatchery (OFishShell).

demonstrates that at worst there is an absence of benefit (although yield foregone to achieve stock conservation benefits could be regarded as an impact). There are, of course, many issues that have not been addressed in this study, notably the near- and far-field environmental and ecological effects that removing energy from marine systems may have. One author predicts dire ecological consequences from some types of tidal energy extraction (van Haren, 2010). Whilst this is not the consensus view for marine renewable energy developments in general, there are currently few hard data available on the topic and it is certainly true that energy extraction is likely to have at least some consequences for physical processes (e.g. Karsten *et al.*, 2008) with implications also for ecological processes. Two priorities can be identified for the future. Firstly, to attempt to identify, in terms of physical and locational variables that can readily be quantified at any given spatial scale (e.g. within a GIS framework), the features of essential fish (and shellfish) habitats, and in particular the relationship of these features with physical variables that are likely to be influenced by marine energy extraction. Secondly, to formulate high-resolution hydrographic models that (i) provide information on the nature of the energy resource, (ii) allow ecological dependencies on physical processes to be identified, and (iii) allow 'what if' questions to be addressed concerning the likely effects on wave and tidal regimes of introducing arrays of wave and tidal energy conversion devices. Work is currently underway at ICIT (Heriot-Watt University) to implement such a model for Orkney Waters and the Pentland Firth using SUNTANS (Fringer *et al.*, 2006). Work on these two priority areas should provide an important substrate for future marine spatial planning decisions concerning fisheries.

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TABLE 1. Results of Fisher exact test for association between sub-rectangles with the top quartile of average tidal or wave power density and the top quartile of commercial fishery, all UK waters. Associations are considered significant at *P*<0.05.

		Wave Power		
		Significant negative association	**Not significant**	**Significant positive association**
Tidal Power	**Significant negative association**	*Nephrops*	Haddock Halibut	Blue Whiting Cod Ling Mackerel Monkfish Saithe
	Not significant	Green Crab Plaice	Squid Whiting	Herring
	Significant positive association	Brown Crab Cockles Lobsters Mussels Queens Sole	Rays	

TABLE 2. Results of Fisher exact test for association between sub-rectangles with the top quartile of average tidal or wave power density and the top quartile of commercial fishery, UK waters inside the 12 mile limit. Associations are considered significant at $P<0.05$.

		Wave Power		
		Significant negative association	**Not significant**	**Significant positive association**
Tidal Power	**Significant negative association**	*Nephrops*		
	Not significant	Mussels Queens	Blue Whiting Brown Crab Cockles Cod Green Crab Haddock Halibut Lobsters Plaice Rays Sole Squid Whiting	Herring Mackerel
	Significant positive association			

TABLE 3. Overlap of 10% of UK wave and tidal energy resources with the value of commercial landings by UK vessels (mean 2000-2009).

	Tidal Energy		**Wave Energy**	
	All waters	**Inside 12 miles**	**All waters**	**Inside 12 miles**
Pelagic	<0.1%	<0.1%	<0.1%	5.6%
Demersal	0.5%	1.0%	<0.1%	0.9%
Shellfish	0.4%	0.4%	<0.1%	1.3%
Total	0.3%	0.5%	<0.1%	1.7%

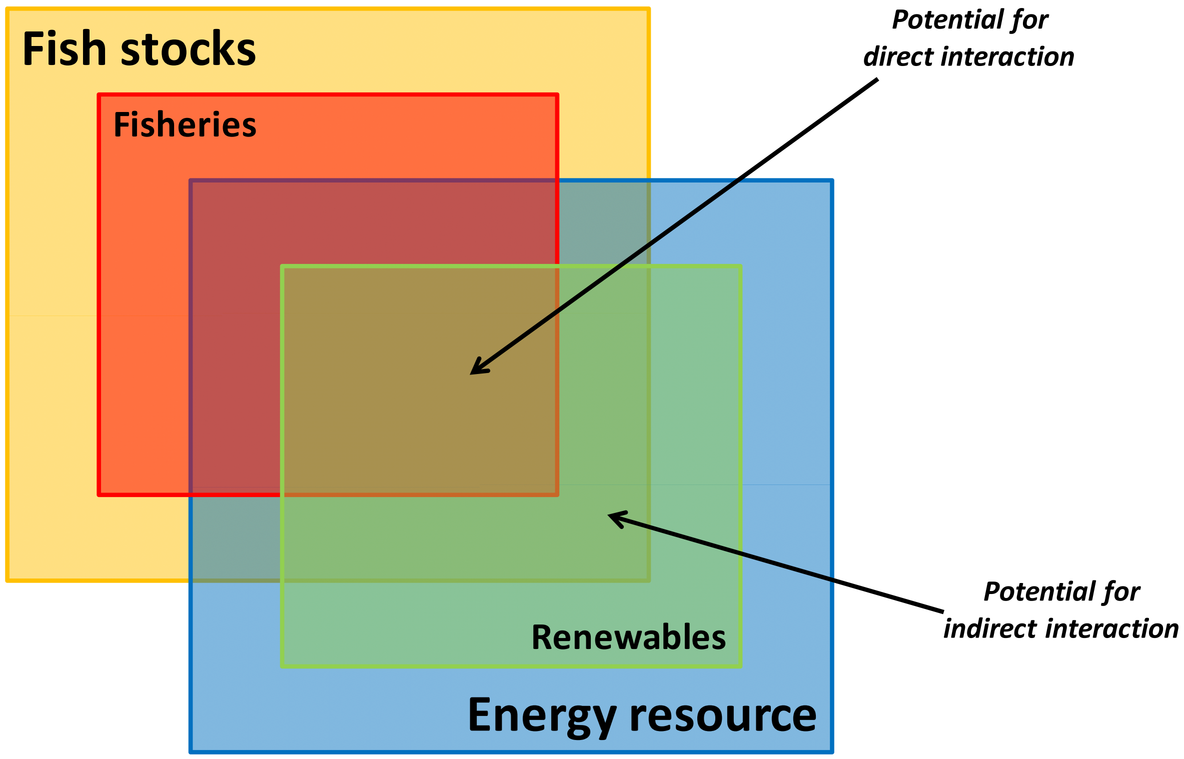


FIGURE 1. Intersections between the spatial domains of fisheries, marine renewable energy developments and the resources on which they depend.

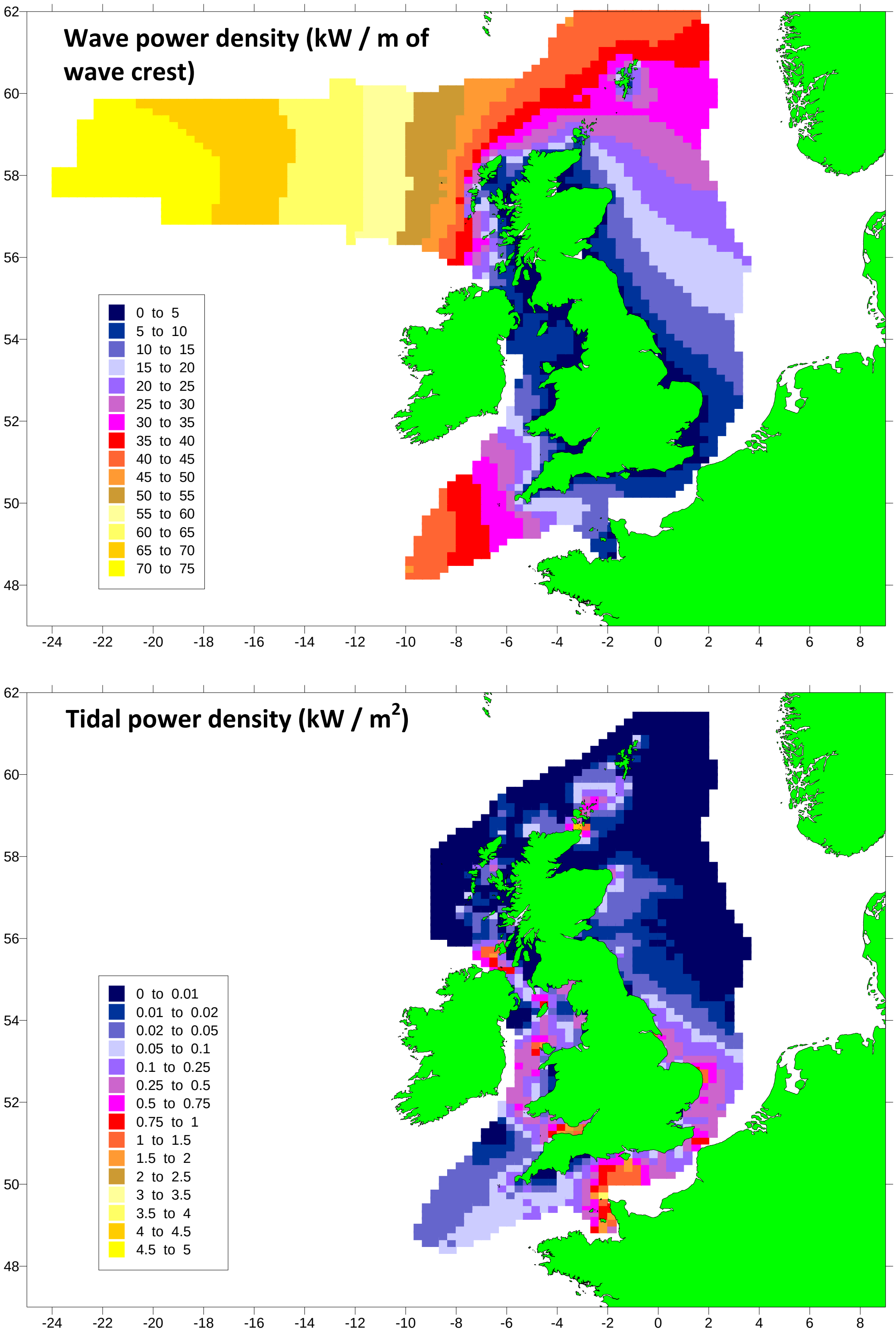


FIGURE 2. Annual mean wave and tidal power density summarised by ICES sub-rectangle, based on data from DTI (2004).

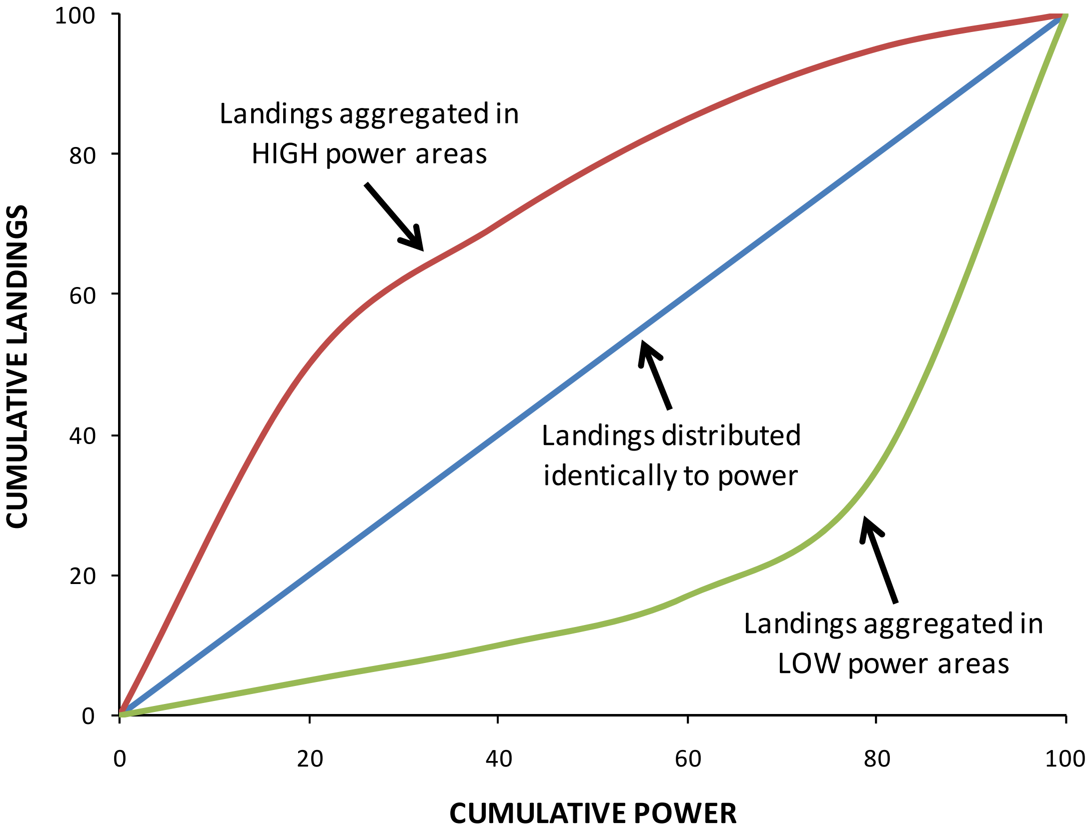


FIGURE 3. Possible curves of cumulative landings against cumulative power, illustrating the distribution of the fishery with respect to the energy resource.

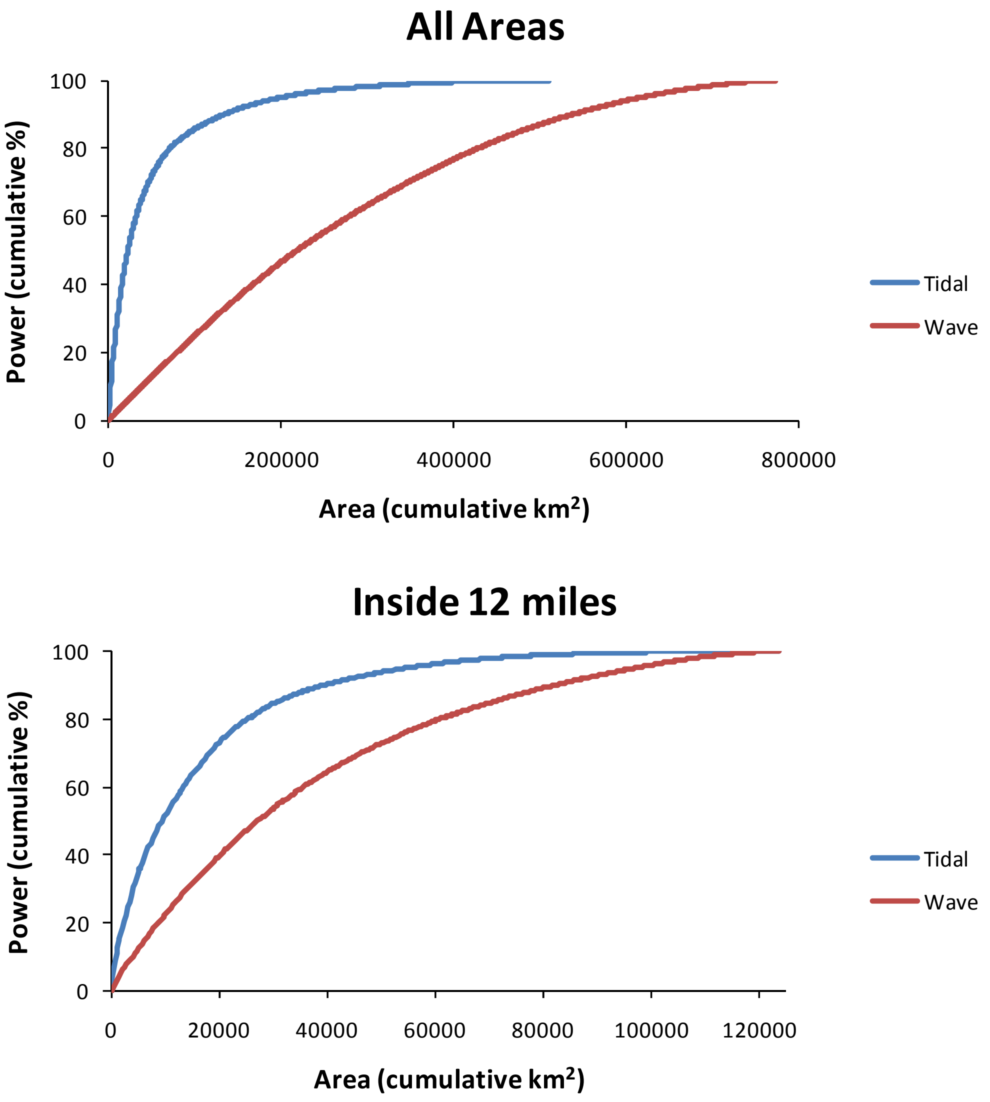


FIGURE 4. Cumulative distribution of UK tidal and wave energy resources, in all UK waters and inside the 12 mile limit.

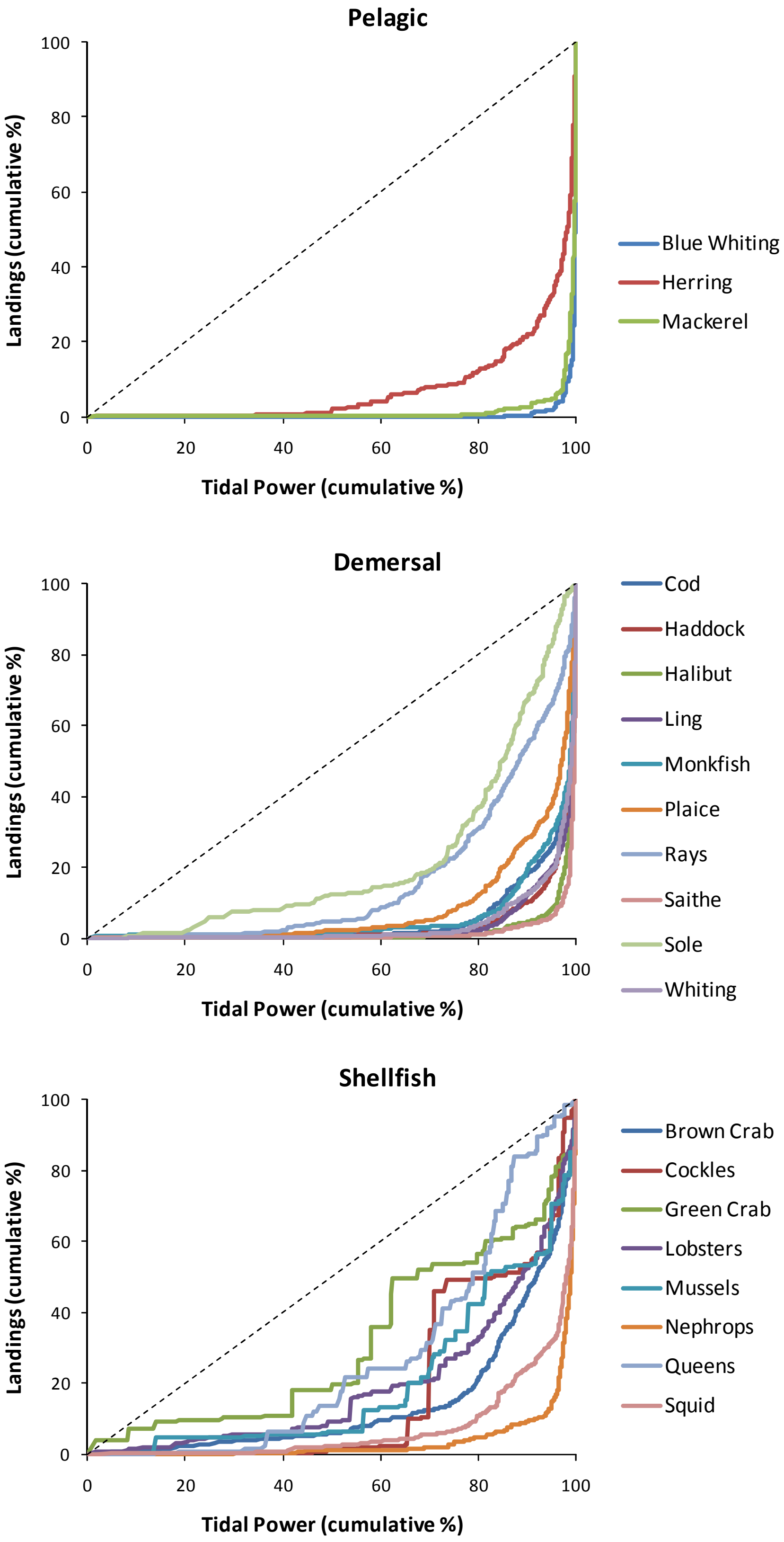


FIGURE 5. Overlap of commercial fishery landings (mean landings by UK vessels, 2000-2009) with UK tidal energy resources.

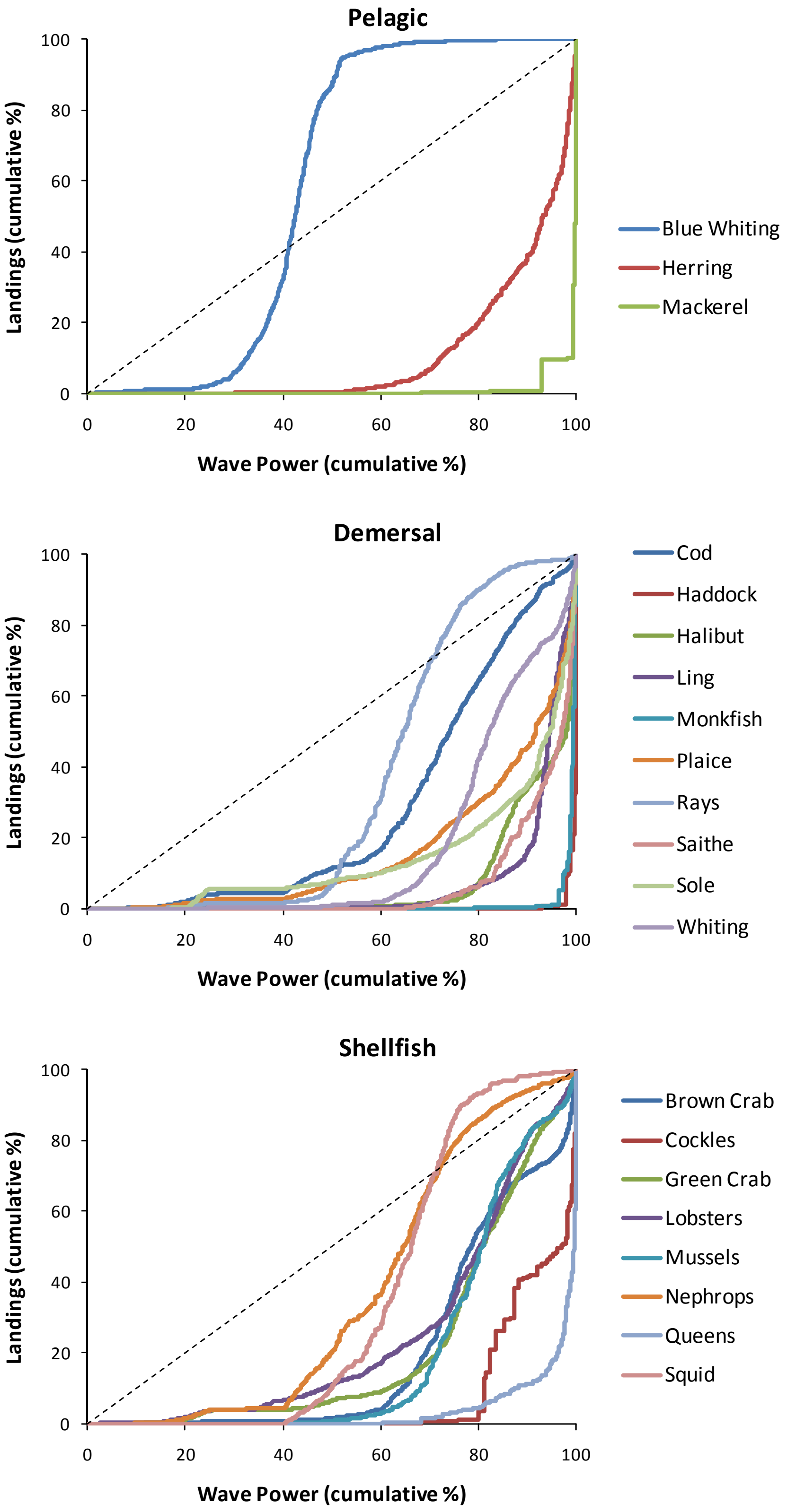


FIGURE 6. Overlap of commercial fishery landings (mean landings by UK vessels, 2000-2009) with UK wave energy resources.

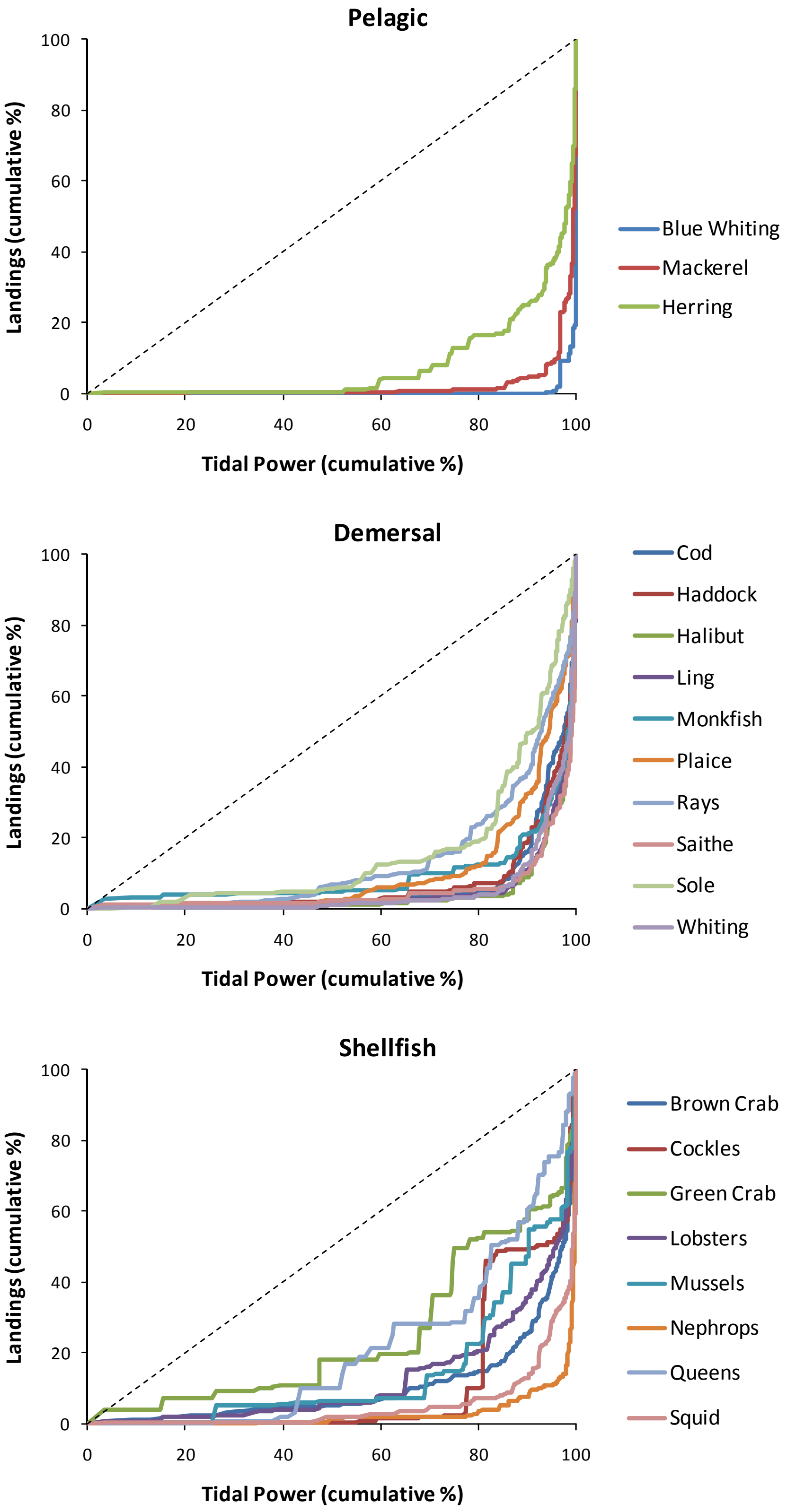


FIGURE 7. Overlap of commercial fishery landings (mean landings by UK vessels, 2000-2009) with UK tidal energy resources inside the 12 mile limit.

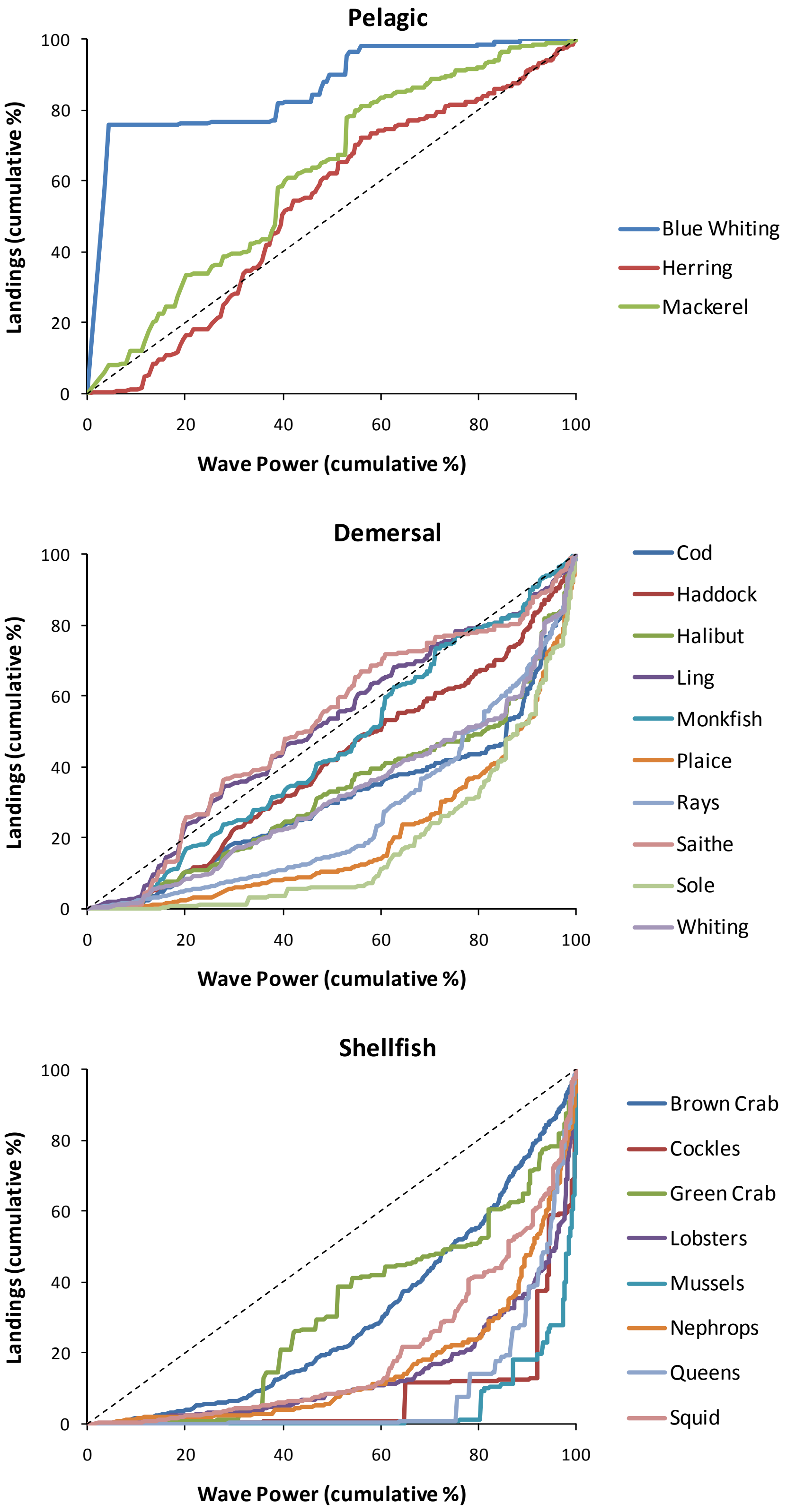
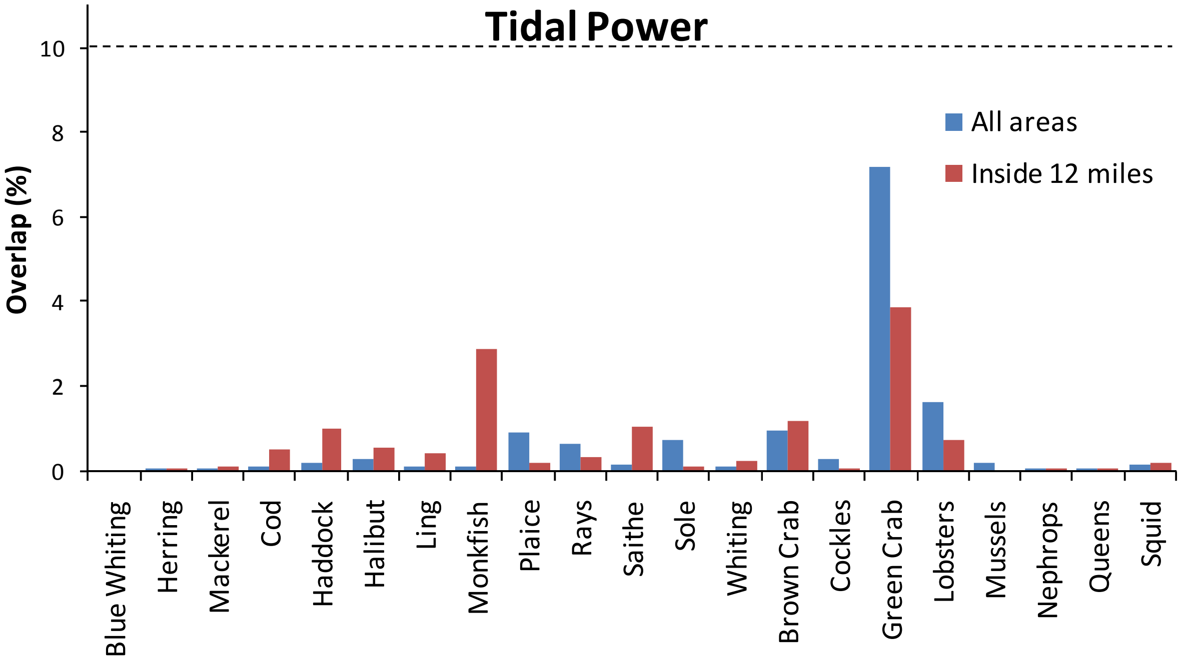


FIGURE 8. Overlap of commercial fishery landings (mean landings by UK vessels, 2000-2009) with UK wave energy resources inside the 12 mile limit.



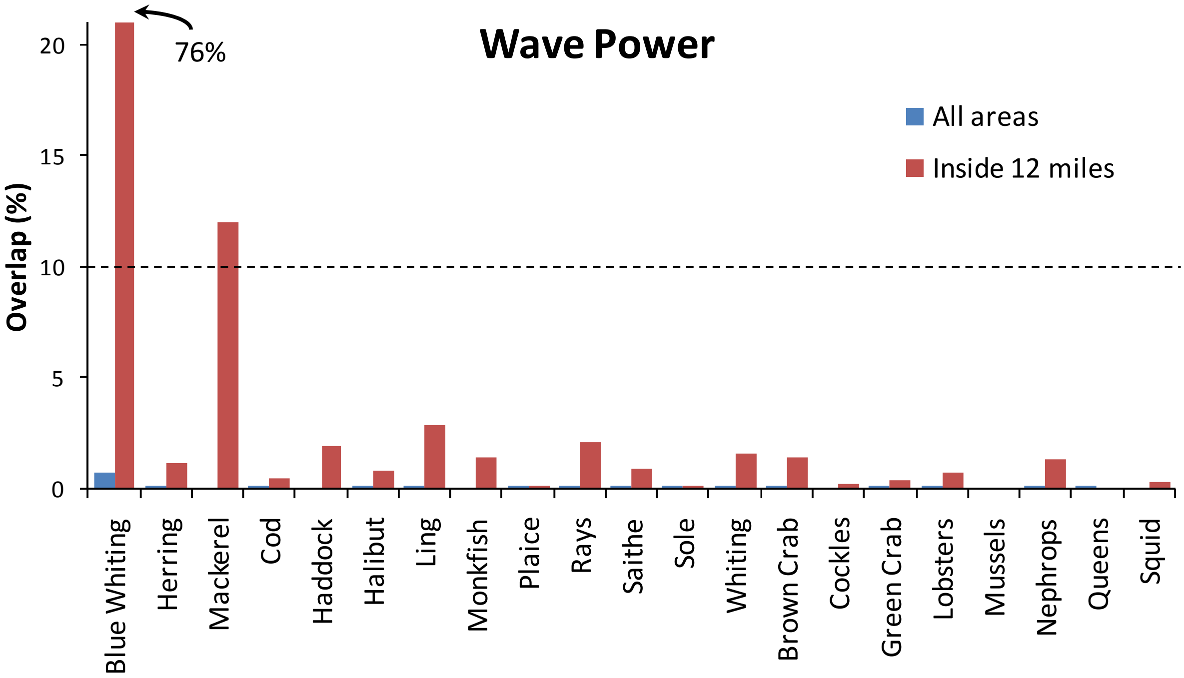


FIGURE 9. Overlap of commercial fishery landings (mean landings by UK vessels, 2000-2009) with 10% of the UK tidal and wave energy resource.

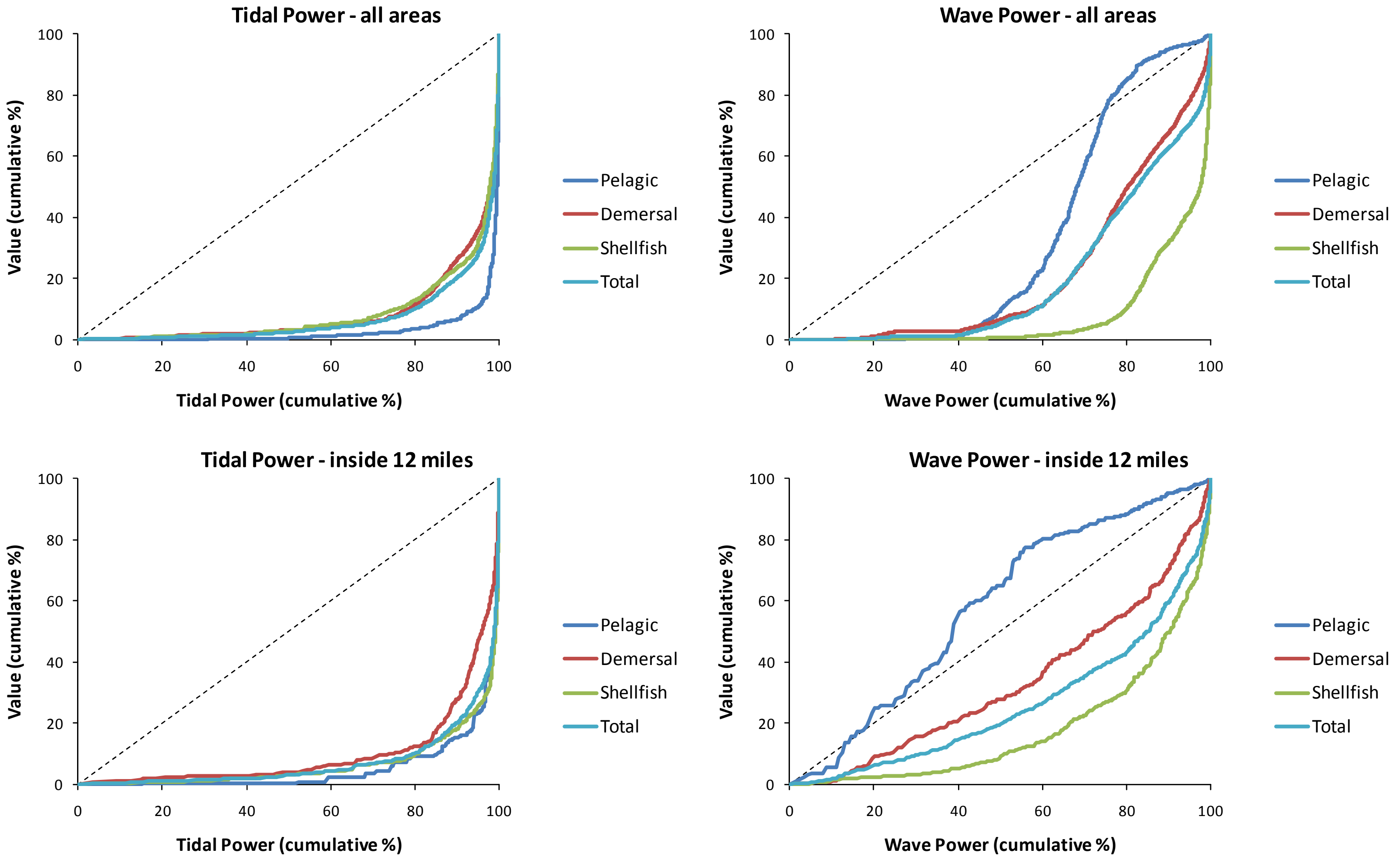


FIGURE 10. Overlap of commercial fishery landings value (mean landings by UK vessels, 2000-2009) with UK tidal and wave energy resources.

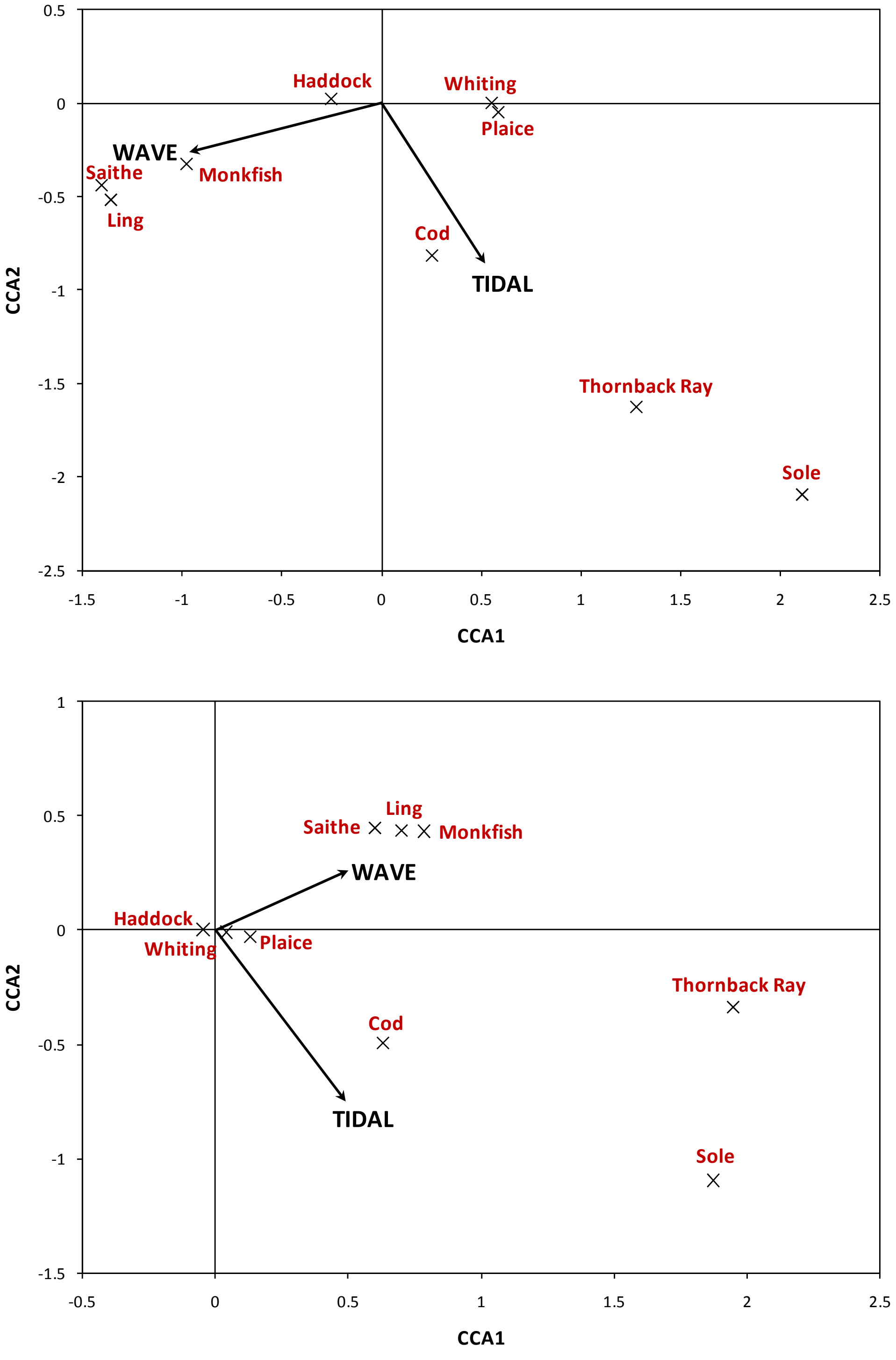


FIGURE 11. Species-environmental biplots for the first two axes of canonical correspondence analyses (CCA) of demersal fish catch per unit effort in weight from International Bottom Trawl Surveys (ALT-IBTS and NS-IBTS, averages for 2000-2009 calculated for sub-rectangles). Environmental variables were wave and tidal energy density. The upper panel shows the results of an unconditional CCA; the lower panel shows the results of a partial CCA, with fish distribution conditional on latitude, longitude and distance from coast.

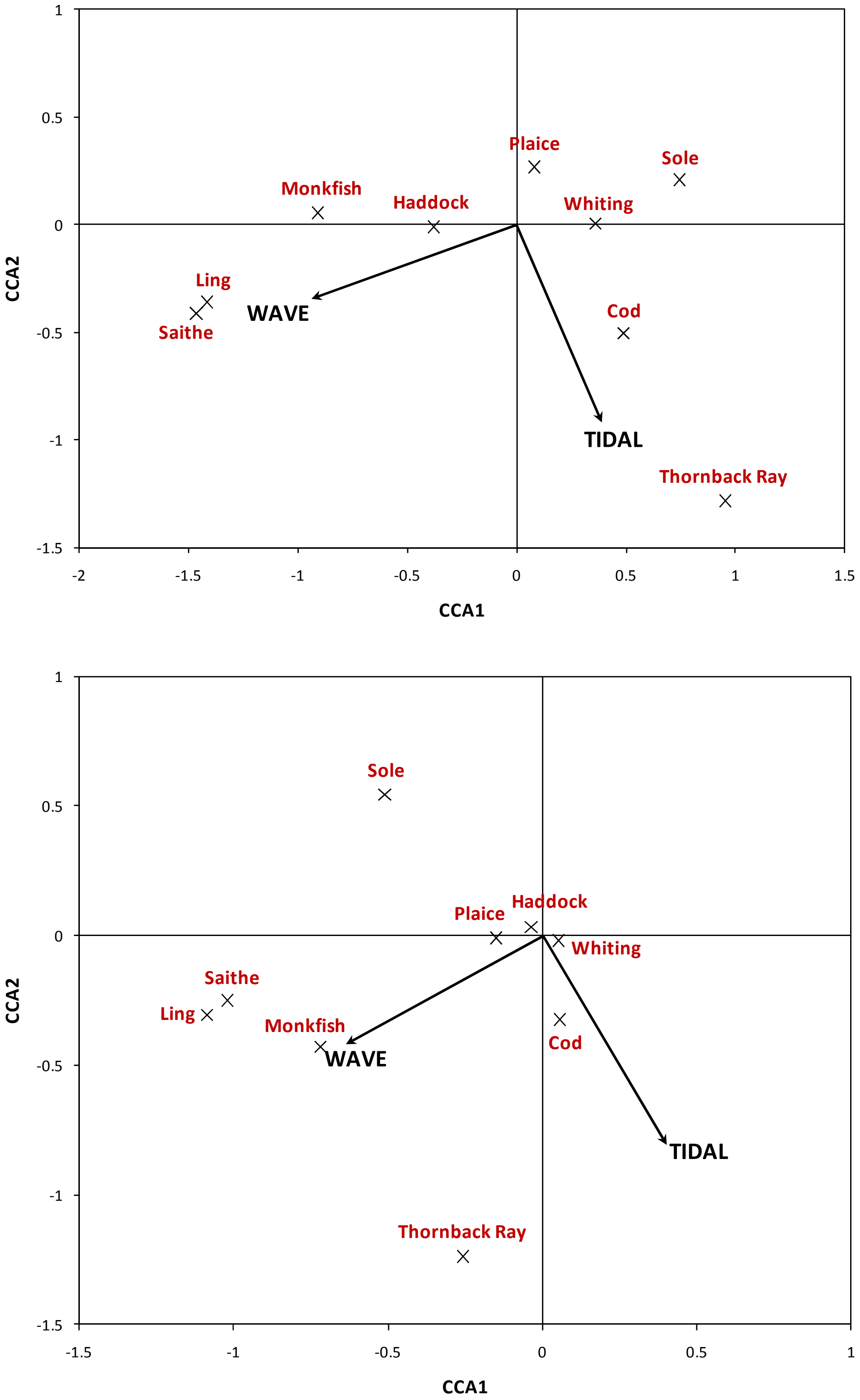


FIGURE 12. Species-environmental biplots for the first two axes of canonical correspondence analyses (CCA) of demersal fish catch per unit effort in weight from International Bottom Trawl Surveys (ALT-IBTS and NS-IBTS, averages for 2000-2009 calculated for sub-rectangles): areas within 12 miles of the coast. Environmental variables were wave and tidal energy density. The upper panel shows the results of an unconditional CCA; the lower panel shows the results of a partial CCA, with fish distribution conditional on latitude and longitude.

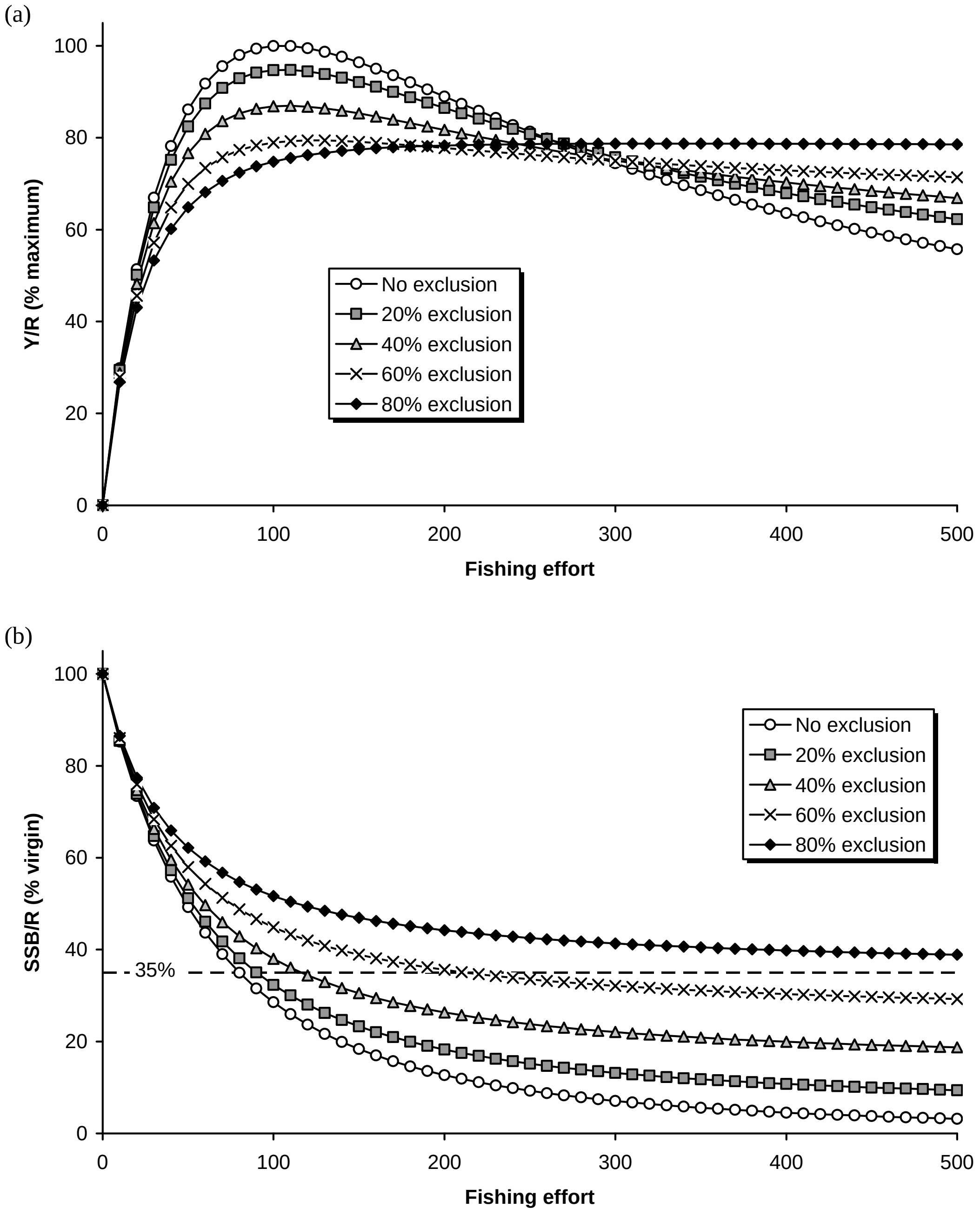


FIGURE 13. (a) Yield per recruit and (b) SSB per recruit curves for different sizes of circular exclusion zone (percentage of stock area). Yield per recruit is expressed as a percentage of the maximum value attained without an exclusion zone. SSB per recruit is expressed as a percentage of the value attained in the absence of exploitation ('virgin' stock). The rate of random movements is selected to be equivalent to an emigration rate of 0.1 from a 20% exclusion zone.

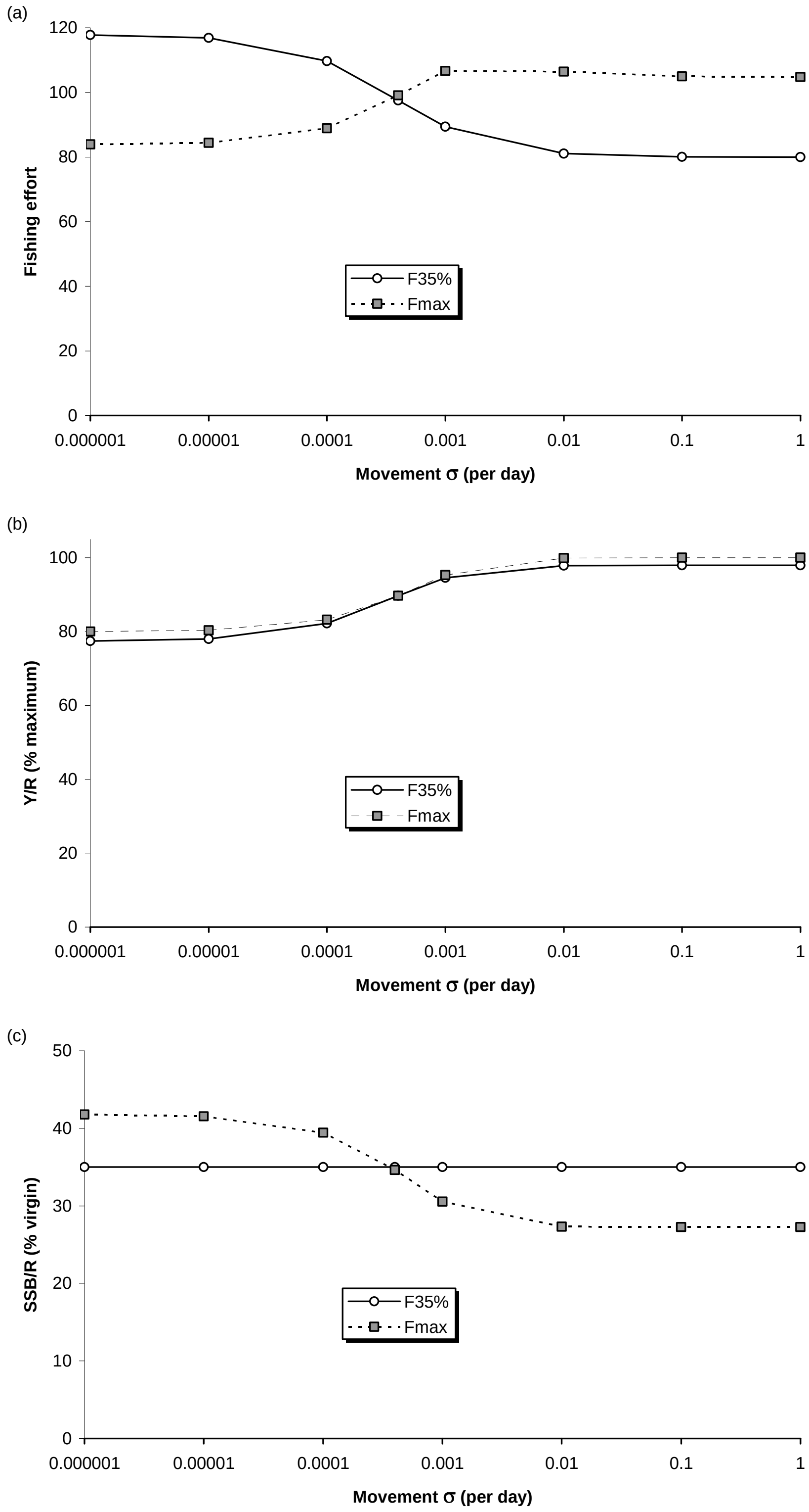


FIGURE 14. (a) Fishing effort, (b) yield per recruit and (c) SSB per recruit at biological reference points of fishing mortality at different movement rates for a circular exclusion zone of 20% (fish movement rate as in Figure 13).

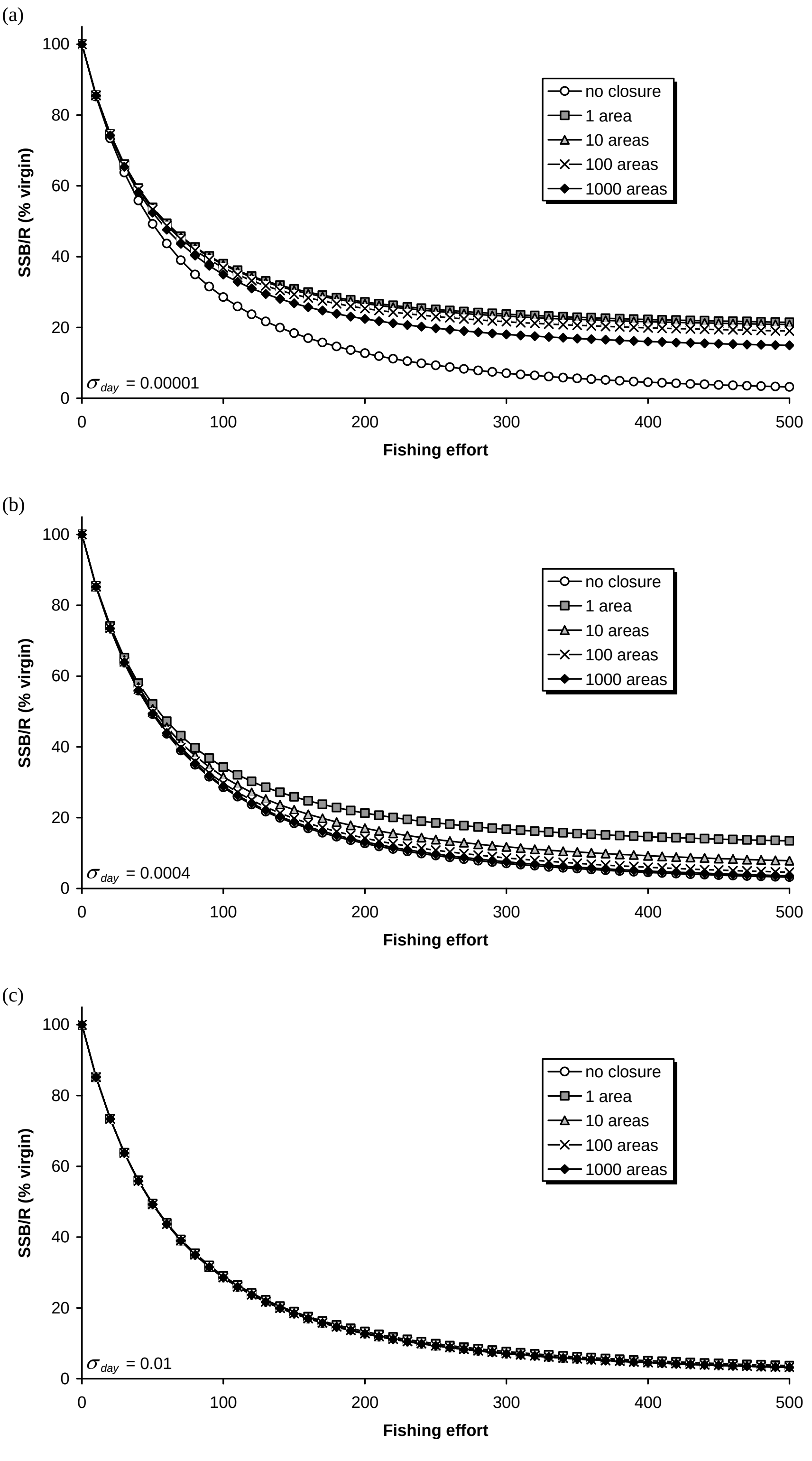
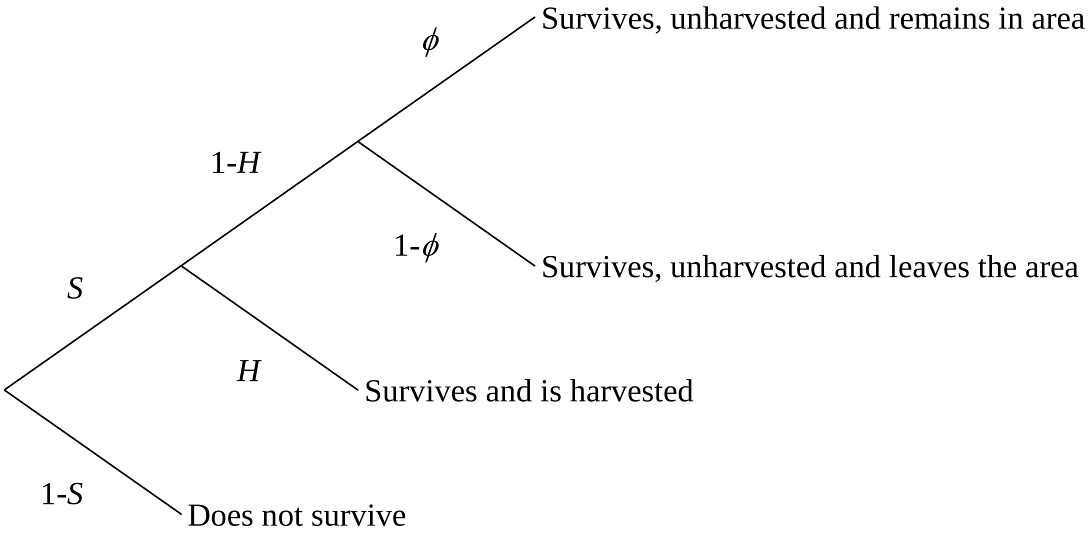


FIGURE 15. SSB per recruit curves for 20% exclusion zones divided into different numbers of circular areas. Curves are shown for (a) low fish movement rate (σ = 0.00001 per day), (b) moderate fish movement rate (σ = 0.0004 per day) and (c) high fish movement rate (σ = 0.01 per day).

APPENDIX I – Spatial fishery models

Stock dynamic models for fishery exclusion zones

Standard fishery models can easily be extended to include fishery exclusion zones. Clearly, fishery and population processes must be treated separately in areas open and closed to fishing. In addition, for all but completely sedentary populations, such models need to consider movements of the target organism between open and closed areas. It is easier to model these exchanges in discrete time steps than to use the standard framework of continuous processes. Over a single time step the fate of a fish in any area can be described in terms of probabilities of surviving natural mortality (S), being harvested (H) and remaining in that area (ϕ):



In the case of a fishery exclusion zone, $H = 0$, so that just three of these fates are possible, involving only S and ϕ parameters.

Transitions between the four possible states within the system – alive in areas open to fishing, alive in fishery exclusion zones, removed by fishing (caught) and dead from natural causes – are easily expressed in matrix form. Over one time step, being the interval between times t and t+1:

$$\begin{bmatrix} N_{open} \\ N_{closed} \\ C \\ D \end{bmatrix}_{t+1} = \begin{bmatrix} S(1-H)\phi_{open} & S(1-\phi_{closed}) & 0 & 0 \\ S(1-H)(1-\phi_{open}) & S\phi_{closed} & 0 & 0 \\ SH & 0 & 1 & 0 \\ 1-S & 1-S & 0 & 1 \end{bmatrix} \times \begin{bmatrix} N_{open} \\ N_{closed} \\ C \\ D \end{bmatrix}_{t} \qquad \text{(Eq. A1)}$$

where N_{open} and N_{closed} are the numbers of fish alive in areas open and closed to the fishery respectively, C is the number of fish removed by the fishery (i.e. catch) and D is the number of fish dead from natural causes. The transitions to D have been included in Eq. A1 for the sake of completeness, so that each column of the transition matrix sums to 1. In practice, however, it is likely that there will be no interest in recording numbers of fish dying from natural causes. It is also likely that the fishery yield in weight is of more interest than the catch in numbers. The modified equation is:

$$\begin{bmatrix} N_{open} \\ N_{closed} \\ Y \end{bmatrix}_{t+1} = \begin{bmatrix} S(1-H)\phi_{open} & S(1-\phi_{closed}) & 0 \\ S(1-H)(1-\phi_{open}) & S\phi_{closed} & 0 \\ SHw_t & 0 & 1 \end{bmatrix} \times \begin{bmatrix} N_{open} \\ N_{closed} \\ Y \end{bmatrix}_t \qquad \text{(Eq. A1a)}$$

where Y is the fishery yield in weight, accumulating in the third element of the state vector, and w_t is the weight of an individual fish at time t (which can be updated for growth over each time step).

The survival and harvest probabilities for discrete time steps can be defined in terms of standard fishery parameters. For daily time steps, the survival rate S is calculated from the annual instantaneous rate of natural mortality, M, by:

$$S = e^{-M/365} \qquad \text{(Eq. A2)}$$

In similar terms, daily harvest rate is calculated as:

$$H = 1 - e^{-\left[\frac{q}{p_{open}} \times \frac{f}{365}\right]} \qquad \text{(Eq. A3)}$$

where q is the catchability coefficient, f is the fishing effort and p_{open} is the proportion of the ground open to fishing. Note that q is spatially scaled, while f is scaled to days. Other types of temporal scaling for f might be appropriate if fishing effort is not evenly distributed through the year or there are temporal as well as spatial controls on fishing. The daily fidelity rates ϕ depend on area size and movement dynamics across the fishing ground, as discussed below.

Side & Jowitt (2005) developed a stock production model based on a similar approach to modelling movements into and out of a closed area. They showed that, for two sub-stocks to be distributed homogeneously, their emigration rates must be in inverse proportion to the carrying capacities of the two areas. In terms of the fidelity rates, the following equality must hold:

$$\frac{(1-\phi_{open})}{(1-\phi_{closed})} = \frac{K_{closed}}{K_{open}} \qquad \text{(Eq. A4)}$$

where K_{closed} and K_{open} are the carrying capacities of the open and closed areas respectively.

Per recruit models

Starting with an arbitrary number of fish, distributed between the open and closed areas of the ground in proportion to their areas, iteration of Eq. A1a over daily time steps between age at recruitment and a maximum age can be used to undertake yield and spawner per recruit calculations. Yield is obtained directly from the final iteration of Eq. A1a, and divided by the starting number of fish to give yield per recruit (*Y/R*). Spawning stock biomass (*SSB*) may also be calculated at each time step, based on the current values of N_{open} and N_{closed} and their weight (w_t) and proportional sexual maturity (m_t) at current age:

$$SSB_t = \left(N_{open.t} + N_{closed,t}\right) \times m_t \times w_t / 365 \qquad \text{(Eq. A5)}$$

The division by 365 reflects daily time steps in the calculations. The sum of SSB_t over all time steps divided by the starting number of fish gives the spawning stock biomass per recruit (*SSB/R*).