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Towards a flexible Decision Support Tool for MSY-based Marine Protected Area design for skates and rays

Simon Dedman[a,b], Rick Officer[a], Deirdre Brophy[a], Maurice Clarke[b], David G. Reid[b]

a Marine and Freshwater Research Centre, Galway-Mayo Institute of Technology, Galway, Ireland; +1 415 944 7258, **b** Marine Institute, Rinville, Oranmore, Co. Galway, Ireland **Emails:** simon.dedman@research.gmit.ie (corresponding author), rick.officer@gmit.ie , deirdre.brophy@gmit.ie , maurice.clarke@marine.ie , david.reid@marine.ie

Abstract

It is recommended that demersal elasmobranchs be managed using spatial proxies for Maximum Sustainable Yield. Here we combine *escapement biomass* – the percentage of the stock which must be retained each year to conserve it – with maps of predicted CPUE of four ray species (cuckoo (*Leucoraja naevus*), thornback (*Raja clavata*), blonde (*R. brachyura*), and spotted (*R. montagui*)), created using Boosted Regression Tree modelling. We then use a Decision Support Tool to generate location and size options for Marine Protected Areas to protect these stocks, based on the priorities of the various stakeholders, notably the minimisation of fishing effort displacement. Variations of conservation/fishing priorities are simulated, as well as differential priorities for individual species, with a focus on protecting nursery grounds and spawning areas. Prioritising high CPUE cells results in a smaller closed area that displaces the most fishing effort, whereas prioritising low fishing effort results in a larger closed area that displaces the least fishing effort. The final result is a complete software package that produces maps of predicted species CPUE from limited survey data, allowing disparate stakeholders and policymakers to discuss management options within a mapping interface.

Keywords

Decision Support Tool DST; Marine Protected Area MPA; Maximum Sustainable Yield MSY; elasmobranch; Boosted Regression Trees BRT; escapement; ray

Abbreviations

- B*pa* – Precautionary reference point for spawning stock biomass
- BRT - Boosted Regression Tree
- CPUE - Catch Per Unit Effort
- DST – Decision Support Tool
- GAM - Generalised Additive Modelling
- GLM - Generalised Linear Modelling
- HR – Harvest Rate
- ICES - International Council for the Exploration of the Sea
- LPUE - Length Per Unit Effort
- MARXAN - Marine spatially Explicit Annealing
- MaxEnt - Maximum Entropy
- MPA - Marine Protected Area
- MSY - Maximum Sustainable Yield
- SSB – Spawning Stock Biomass
- TAC – Total Allowable Catch
- WGEF - Working Group for Elasmobranch Fisheries

1 Introduction

The large size and low fecundity of elasmobranchs such as rays makes them especially vulnerable to fishing pressure (Baum et al., 2003; Ellis et al., 2005b; Worm et al., 2013), and decades of high fishing effort have reduced the size, range, and diversity of Irish Sea rays (Brander, 1981; Rogers and Ellis, 2000; Walker and Hislop, 1998) such that these data-limited stocks require appropriate fisheries management in order to reach Maximum Sustainable Yield (MSY) by 2020 (European Commission, 2013). Not only is it important to manage species to MSY because it’s a minimally precautionary target to ensure stocks and biodiversity are maintained (Kaplan and Levin, 2009; Levin et al., 2009; Zabel et al., 2003), but we are legally mandated to do so by 2015, 2020 at the latest (European Commission, 2013). Traditional Total Allowable Catch (TAC) based limits are often difficult to operationalise for species such as elasmobranchs, generally due to data deficiencies, particularly on catches, among other reasons (Ellis et al., 2010; ICES WGEF, 2012a). For this reason, spatial management is an alternative approach recommended (ICES WGEF, 2012a; NWWRAC, 2013). Spatial management tools explored by ICES WGEF (2012b) have been further developed (Dedman et al., 2015) using Boosted Regression Trees (BRT). BRTs outperform many other statistical methods (Elith et al. (2006), see also Dedman et al. (2015), in review for comparisons). They have a demonstrated ability to reveal species-level Catch Per Unit Effort (CPUE) maps for the Irish Sea based on limited data (Dedman et al., 2015), to identify candidate nursery ground and spawning areas (Dedman et al., In Review), as well as amalgamate conservation priority areas for four species of differing vulnerability (Table 1).

Species	Area	Fishing pressure	Stock size	%SSA	Total V.	Scaled ratio	V. Rank
Blonde ray	VIIa,f,g	Overexploited: 1	Unknown: 1	0.5	2.5	4.17	1
Cuckoo ray	VI, VII	Overexploited: 1	Decreasing: 1	0.1	2.1	3.5	2
Spotted ray	VIIa, e-h	Overexploited: 1	Increasing: 0	0.4	1.4	2.33	3
Thornback ray	VIIa, f, g	Appropriate: 0	Increasing: 0	0.6	0.6	1	4

Table 1: Conservation status, percent of spawning in study area, and vulnerability of key Irish Sea rays (ICES WGEF, 2014) with calculated total vulnerability metric, ratios from scaling the least vulnerable to 1, and rank

Locating areas of essential habitat for species is a key step in the process towards spatial management (Foley et al., 2010; Kelleher, 1999). However, implementing area closures, for example by creating Marine Protected Areas (MPAs), must be based on robust biological knowledge in order to correctly size and locate the closed areas, to maximise their chances of success (Agardy et al., 2011; Kelleher, 1999). In this study we demonstrate a method that links fishing mortality reference points (i.e. F_{MSY}) to life history traits (Zhou et al., 2012), as applied to these species by Shephard et al. (2015). This results in a per-species Harvesting Rate (HR_{MSY}), i.e. the percentage of the total stock biomass which can be sustainably removed each year. The inverse of this is therefore the percentage of total stock biomass which must be *retained* each year – the *escapement biomass*. Protecting that proportion of each species in the study area should protect the Irish Sea element of the stocks. So species that have a higher proportion of their spawning stock in the Irish Sea, e.g. blonde rays (Table 1) should be the main priority.

A key objective in MPA design might be to minimise fishing fleet disruption and effort displacement by considering the impact on fisheries (Agardy et al., 2011; Klein et al., 2013; Suuronen et al., 2010), not least because displaced effort can have unpredictable and often negative consequences on the stocks (Baum et al., 2003; Penn and Fletcher, 2010). Stakeholder involvement is an important consideration in MPA design (Kelleher, 1999). It increases the likelihood of compliance (Agardy et al., 2011), without compromising conservation goals (Klein et al., 2013). Giving fishermen and policy-makers equal access to Decision Support Tools (DST) enables all parties to explore spatial management options without compromising scientific quality, increasing the shared ownership of conservation outcomes.

2 Aims

Here we use the estimated proportions of population biomass that must be conserved annually to meet MSY (via HR_{MSY})(Shephard et al., 2015) and combine that information with fishing effort data and modelled ray CPUE maps to identify the location and size of habitat areas where management could protect the escapement biomass, while minimising disruption to fishing activity and the displacement of effort. We do this under a range of exploitation and conservation scenarios then propose a target-based rationale for the size and location of protected areas for Irish Sea skates and rays, and present a DST that allows fishermen and policymakers to evaluate closed area options.

3 Methods

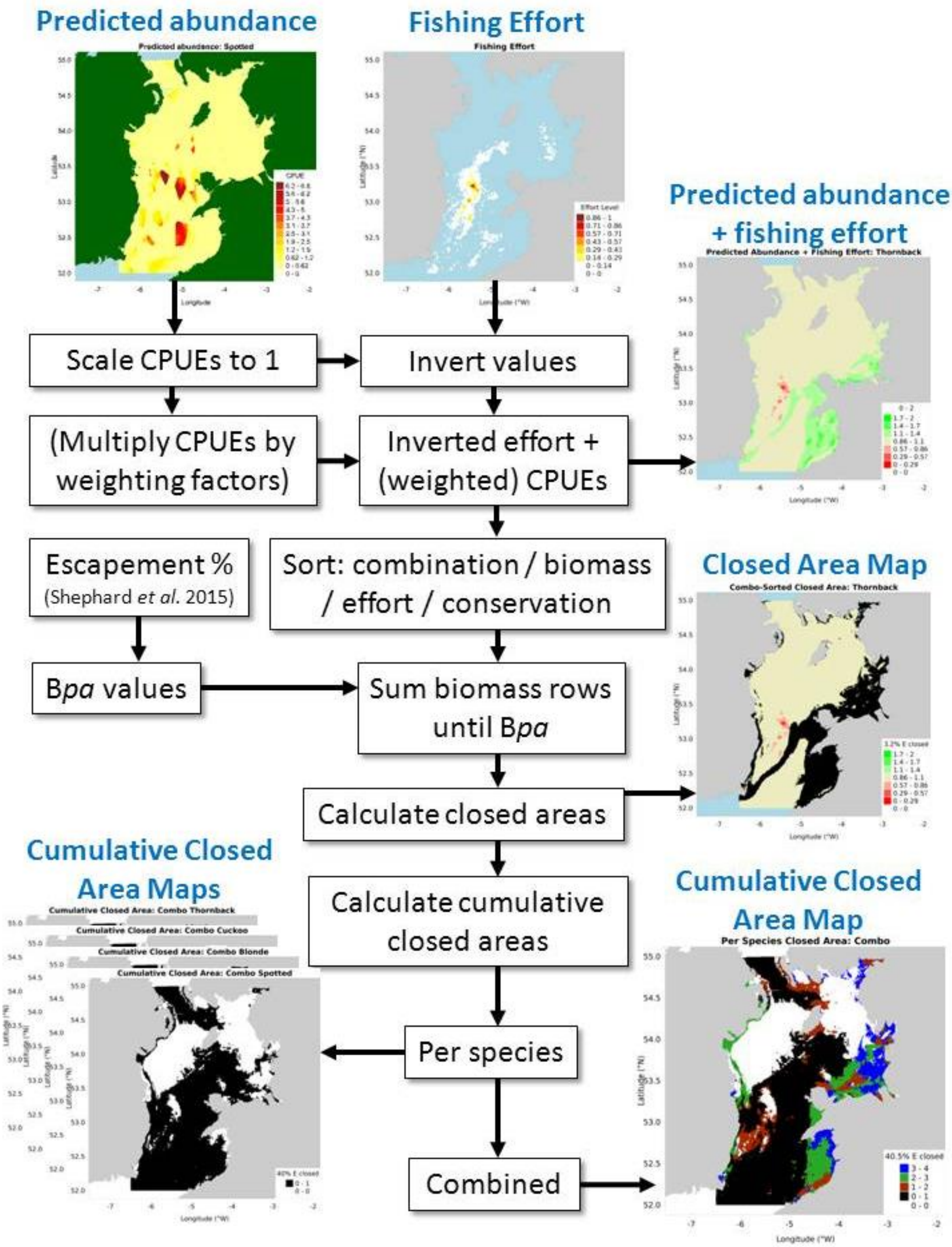

Figure 1: Conceptual diagram of B*pa* closed area approach

The BRT-predicted CPUE maps were normalised to a 0 to 1 scale and multiplied by per-species weighting factors, if required, for fishing versus conservation, and/or individual species conservation weightings. Fishing effort was inverted and also normalised, from 0 for maximum effort to 1 for no effort. This was then added to the CPUEs, creating a combination metric running from 0 (no CPUE and maximum effort) to 2 (maximum CPUE and no effort). To evaluate alternative management priorities, species data were sorted in four different ways:

- the aforementioned combination metric, high to low (*Combination Sort*)
- CPUE only, high to low, emphasising protecting high biomass areas (*Biomass Sort*)
- fishing effort data only, low to high, emphasising protecting low fishing effort areas (*Effort Sort*)
- conservation data, high to low, emphasising protecting high conservation areas (*Conservation Sort*)

Weighting only affects the Combination Sort, since the combination metric is a product of CPUE and effort, and the relationship between these is changed by the weighting process.

After the full dataset was sorted according to the desired schema (above), the model cumulatively summed down the species CPUE rows until reaching the HR_{MSY} proportion of the species' total. HR_{MSY} values for cuckoo, thornback, and spotted ray were taken from Shephard et al. (2015); the value for blonde ray, 0.08, was derived using Shephard's method. These summed rows in the dataset will contain the escapement biomass and the cells represented by these rows are thus the candidate closed area. These are then mapped over the combination metric background, producing one map per species. Displaced effort is calculated as the effort in the closed cells, and expressed as a percentage of total effort in the map legend.

Cumulative closed area maps are then calculated for each sort type, starting with the most vulnerable species. The first species' closed area is calculated as before, then extended for the second species, cumulatively summing that species' biomass rows until its HR_{MSY} proportion is reached, but starting with the first species' rows already selected. That is, the process starts by summing the species 2 biomass contained within the species 1 closed area, then expands the species 1 closed area until it reaches the HR_{MSY} proportion for species 2 as well. This process is repeated for all species in descending order of vulnerability. In some cases a species' HR_{MSY} proportion may already be met by the cumulative closed area calculated for the previous species. In this study, the HR_{MSY} is a theoretical concept, because we only consider a subset of the extent of the four ray stocks.

To compare outcomes of the Combination Sort under different management strategies, we tested four different conservation:fishing weighting scenarios. These were:

- Parity of biomass and fishing (1:1 ratio for all species)
- Primacy of conservation over fishing (10:1 ratio for all species)
- Primacy of fishing over biomass (1:10 ratio for all species)

In addition, we investigated the consequences of differing species conservation priority by applying species-specific vulnerability weightings. These were derived from ICES WGEF (2014) conservation status metrics, with negative elements being given a score of 1, and positive elements 0. The elements were fishing pressure, stock size, and the percent which each species/stock spawns in study area. These were then added together to give a total vulnerability score of 2.5, 2.1, 1.4 and 0.6 for blonde, cuckoo, spotted and thornback ray respectively. These scores were then scaled to align the least vulnerable (thornback ray) to 1, i.e. by dividing each by 0.6, to give final ratios of 4.17, 3.5, 2.33 and 1 respectively (see Table 1), with fishing effort also given a weighting value of 1. The effect of this is that thornback ray is given equal importance to fishing, whereas the other three species are varying degrees of greater importance.

The predicted-CPUE map inputs were generated using the delta log-normalised BRT-predicted CPUE mapping approach described in Dedman et al. (2015). This method machine-learns the relationship between six environmental variables (temperature, depth, salinity, current speed, substrate grain size, distance to shore), commercial fishing effort (average annual ray LPUE from demersal trawls (Kg-Hr), 2006-2012, Marine Institute), and ray CPUE from 1447 fishery-independent survey sites (International Council for Exploration of the Sea (ICES) International Bottom Trawl Survey (IBTS) series (ICES, 2015)) then predicts ray CPUE to the remainder of the Irish Sea based on the environmental variable values there. These environmental variables are known covariates to elasmobranch abundance (Ellis et al., 2005a; Kaiser et al., 2004; Lauria et al., 2015; Martin et al., 2012) that were recently proven to be influential in predicting ray abundances in the Irish Sea (Dedman et al., 2015). Fishing may be the primary human activity driving marine distributions (Worm et al., 2006), but human impact variables may be of lesser importance for these species in this area (Dedman et al., 2015; Navarro et al., 2016), or co-depend on environmental and spatial factors (Navarro et al., 2015). The fishing effort data layer only patchily covers the Irish Sea, predominantly in an area running down the Irish coast (see Figure 1) – this reflects the activity of the fleet. Prey availability is known to affect elasmobranch distribution (Navarro et al., 2016) but the primary source of such data would be the patchy-coverage ICES IBTS already used for the response variable. Since these are demersal predators (Ajayi, 1982; Ellis et al., 1996), substrate, depth, temperature and other environmental variables are expected to serve as predictive variables to the distribution of their prey communities (EMODnet, 2016).

The conservation maps were produced by scaling the BRT-predicted CPUE maps (Dedman et al., 2015) values’ to 1 by dividing them all by the maximum value, then adding them together, resulting in a single surface of predicted conservation importance for these four rays in the Irish Sea (as per Dedman et al. (In Review)). Predicted CPUE maps and conservation maps were generated using survey data and CPUE covariates as per Dedman et al. (2015), and juvenile ray and eggcase-reducing variables (predatory fish CPUE, fishing effort, scallop dredging effort, whelk CPUE) per Dedman et al. (In Review). The table of datasets used, their sources and resolutions from Dedman et al.

(In Review), including the datasets used in Dedman et al. (2015) and thus covering all input data underpinning this study, is reproduced in the supplementary material (Table 4).

Cuckoo rays prefer sandy substrates away from shore at 70 - 100m depths (Dedman et al., 2015; Ellis et al., 2005a; Marine Institute, 2012; Wheeler, 1978; Whitehead et al., 1984). Thornback rays have a wider range of depth preferences (10 - 300m) with juveniles inshore and adults 16 – 24km away, preferring gravel and pebble banks with mid- to strong current speed (Dedman et al., 2015; Ellis et al., 2005a; Fahy and O'Reilly, 1990; Kaiser et al., 2004; Lauria et al., 2015; Martin et al., 2012; Stehmann and Bürkel, 1984). Blonde rays prefer to inhabit offshore sandbanks and coastal shallows (Dedman et al., 2015; Kaiser et al., 2004; Martin et al., 2012). Spotted rays prefer 30 – 150m depth sandy substrates (Dedman et al., 2015; Ellis et al., 2005a; Fahy and O'Reilly, 1990; Martin et al., 2012). Peak egg laying periods for these species are within the spring and summer months (Clark, 1922; Gallagher, 2000; Ryland and Ajayi, 1984); juveniles are virtually sedentary (Gallagher, 2000; Holden, 1975; Steven, 1936; Templeman, 1984), but adults often migrate inshore to breed and spawn (Ryland and Ajayi, 1984; Steven, 1936; Walker and Ellis, 1998).

4 Results

The method of inverting scaled fishing effort and adding it to scaled CPUE maps results in maps that clearly show the best and worst areas to close in order to protect each species while minimally disrupting the fishery (Figure 2).

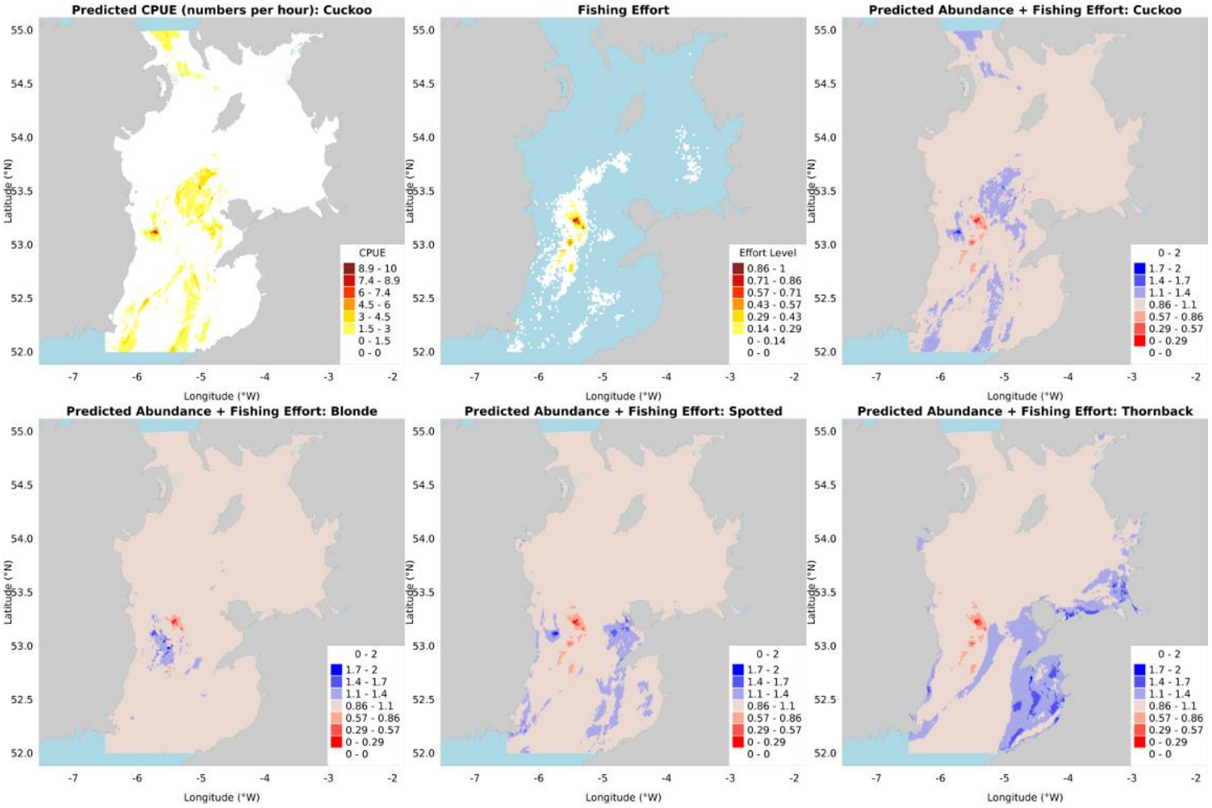

Figure 2: Maps of modelled CPUE then fishing effort for cuckoo ray, and CPUE plus inverted fishing effort both scaled to 1 (higher value areas are good to close, lower value are bad) for cuckoo, blonde, spotted and thornback ray

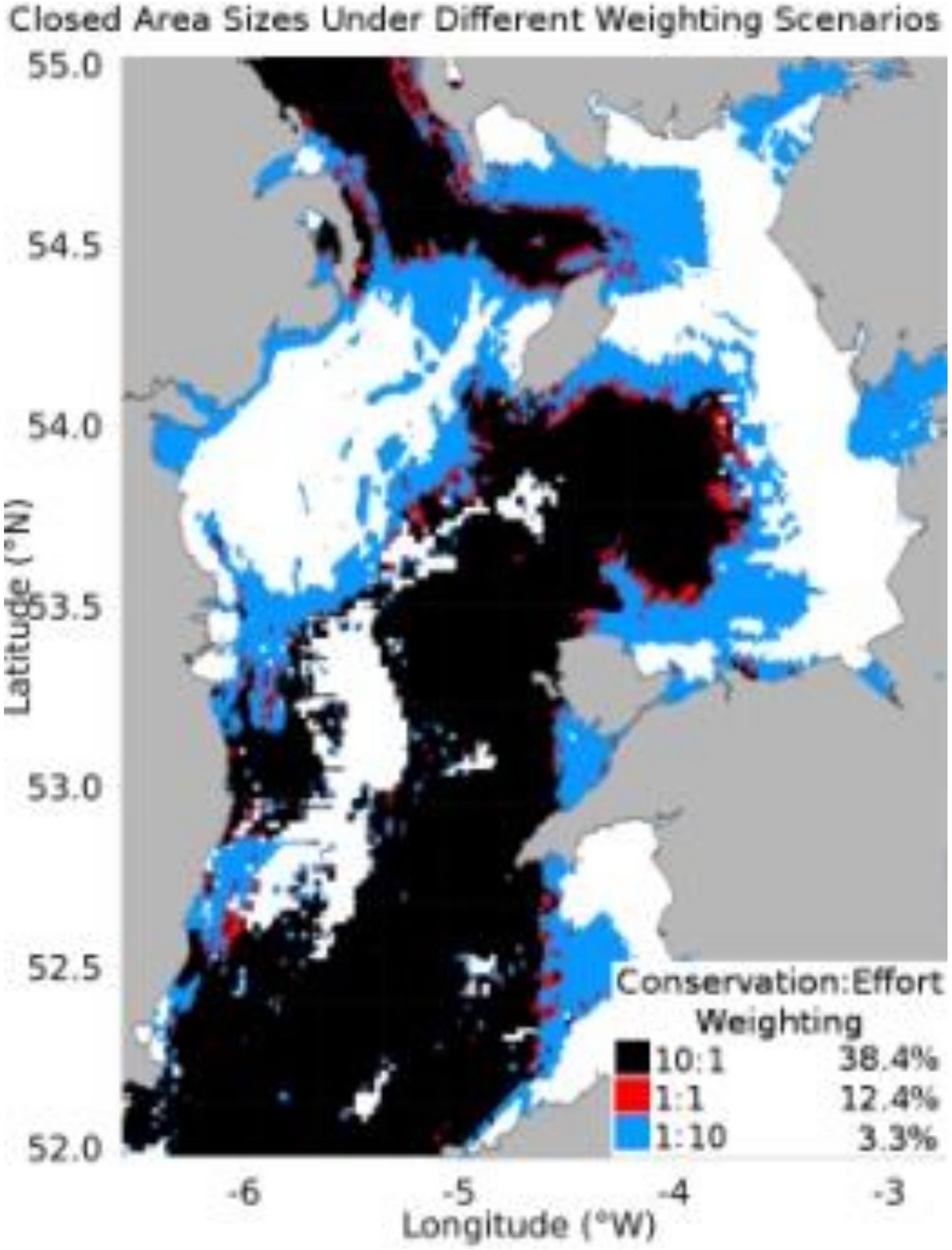

Figure 3: Maps of cuckoo ray closed areas prioritising combinations of conservation and fishing effort, with conservation:effort weightings of 10:1, 1:1 and 1:10 and corresponding loss of fishing effort percentages. Note that layers mostly overlap i.e. 1:10 includes both 1:1 and 10:1, 1:1 includes 10:1.

Altering the rays CPUE:effort weighting markedly affects the amount of effort displaced by the closed area, and the size of those closed areas, as anticipated (Figure 3). For cuckoo ray, 12.4% of effort is displaced by the area closure required to reach theoretical B*pa* for this species when both ray CPUE and fishing effort are scaled to 1 and combined (1:1 ratio). Giving the rays a weighting of 10 (10:1 ratio) shifts some of the area closure onto areas of fishing effort, resulting in a total displaced effort of 38.4% but a smaller area closure. Prioritising effort (1:10 ratio) results in only 3.3% displaced effort, with the closed area avoiding sites of even low effort thus expanding across a greater area of moderate ray CPUE. In conclusion we can see that prioritising high CPUE cells results in a smaller closed area that displaces the most fishing effort, whereas prioritising low fishing effort results in a larger closed area that displaces the least fishing effort.

	Ray : Effort Weighting			
Species	**1:1**	**1:10**	**10:1**	**(4.17, 3.5, 2.33, 1)*:1**
Blonde	34.7	24.5	90.1	73.4
Cuckoo	12.4	3.3	38.4	20.4
Spotted	7.3	1.6	19	10.9
Thornback	3.2	1	5.3	3.2
Blonde Cumulative	34.7	24.5	90.1	73.4
Cuckoo Cumulative	39.5	24.5	93.8	77.6
Spotted Cumulative	40	24.5	94.2	77.9
Thornback Cumulative	40.5	24.5	94.6	78.3

*for blonde, cuckoo, spotted and thornback ray respectively

Table 2: Fishing effort (%) displaced by the closed areas of different ray:effort weightings, using the Combination Sort

Table 2 shows the percentages of fishing effort that closed areas displace under different weighting scenarios, within the Combination Sort scenario. These are given for individual species and cumulative (multiple) species area closures. Weighting in favour of rays produces the highest displacement of effort (95 and 78% respectively). Weighting in favour of effort results in less displacement than weighting 1:1, as expected (25 and 41% respectively). One can see the effect of the weighting process when comparing the individual-species closed area displacements for the 1:1 ray scores to the per-species weightings: blonde and cuckoo ray have weightings of 4.17 and 3.5 respectively, which sees the effort their closures displace rising from 35 to 73%, and 12 to 20% respectively. Spotted and thornback ray have lower weightings (2.33 and 1 respectively) which sees spotted ray's displacement rise from 7 to 11 and thornback ray's obviously unchanged. So again, prioritising effort displaces less effort, prioritising conservation displaces more.

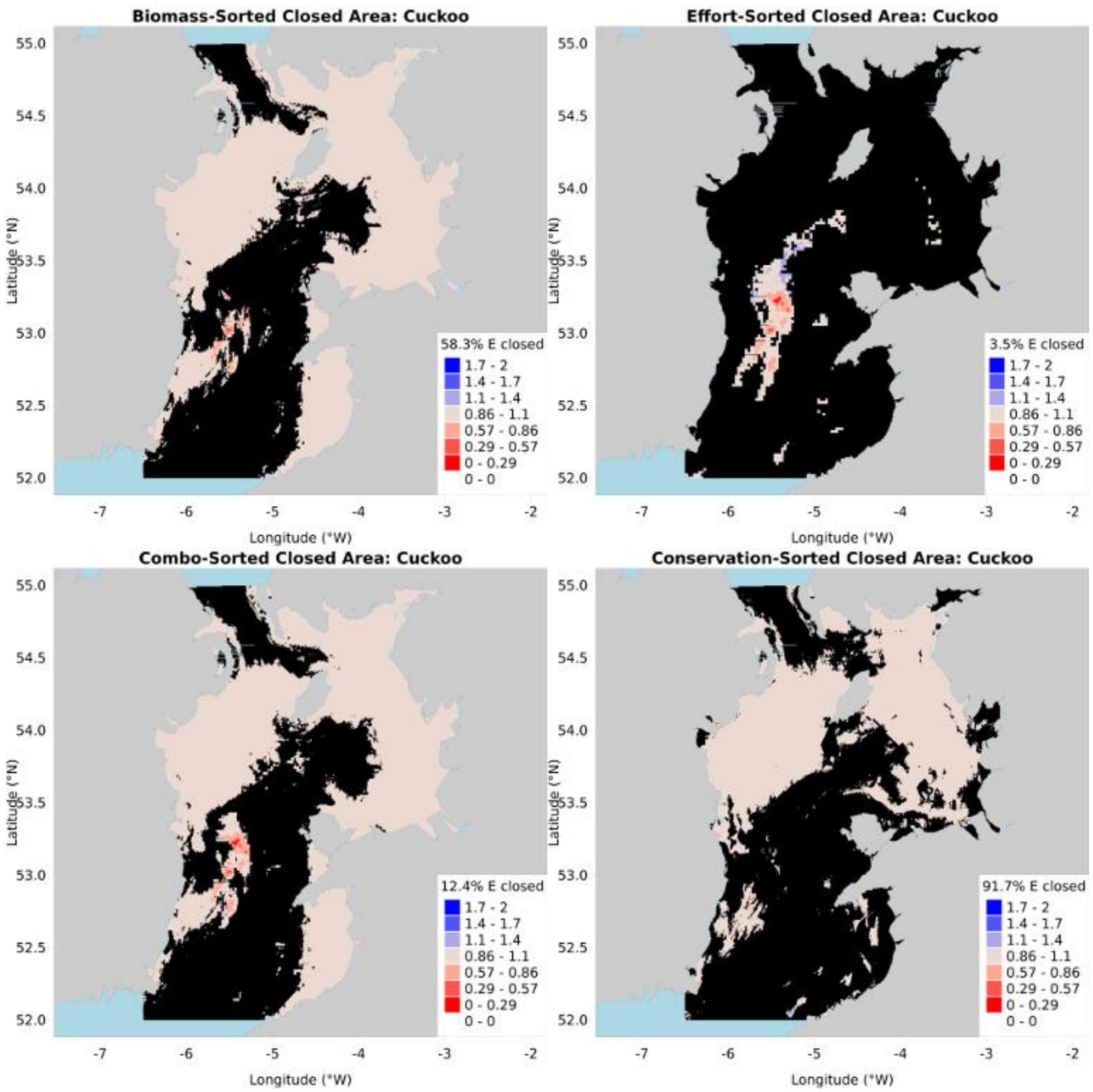

Figure 4: Maps of cuckoo ray closed areas prioritising species biomass, fishing effort, a combination of both, and conservation areas

With the default 1:1 ratio of ray CPUE to fishing effort, the closed areas produced by the different sorting strategies are displayed in Figure 4, again for cuckoo rays only (see Supplementary Material for all species). The Biomass Sort displaces 58% of the fishing effort and covers a large area, tightly bunched around the high fishing effort area fringes then spread over the deep water areas. The Effort Sort displaces only 4% of the effort, but closes a larger area. The Combination Sort displaces 12% of the effort while still closing a very similar area to the Biomass sort. The Conservation Sort displaces 92% of the effort and closes much of the Irish Sea. Evidently, then, the Combination Sort achieves the best combination of small closed area but also reduced displacement of fishing effort.

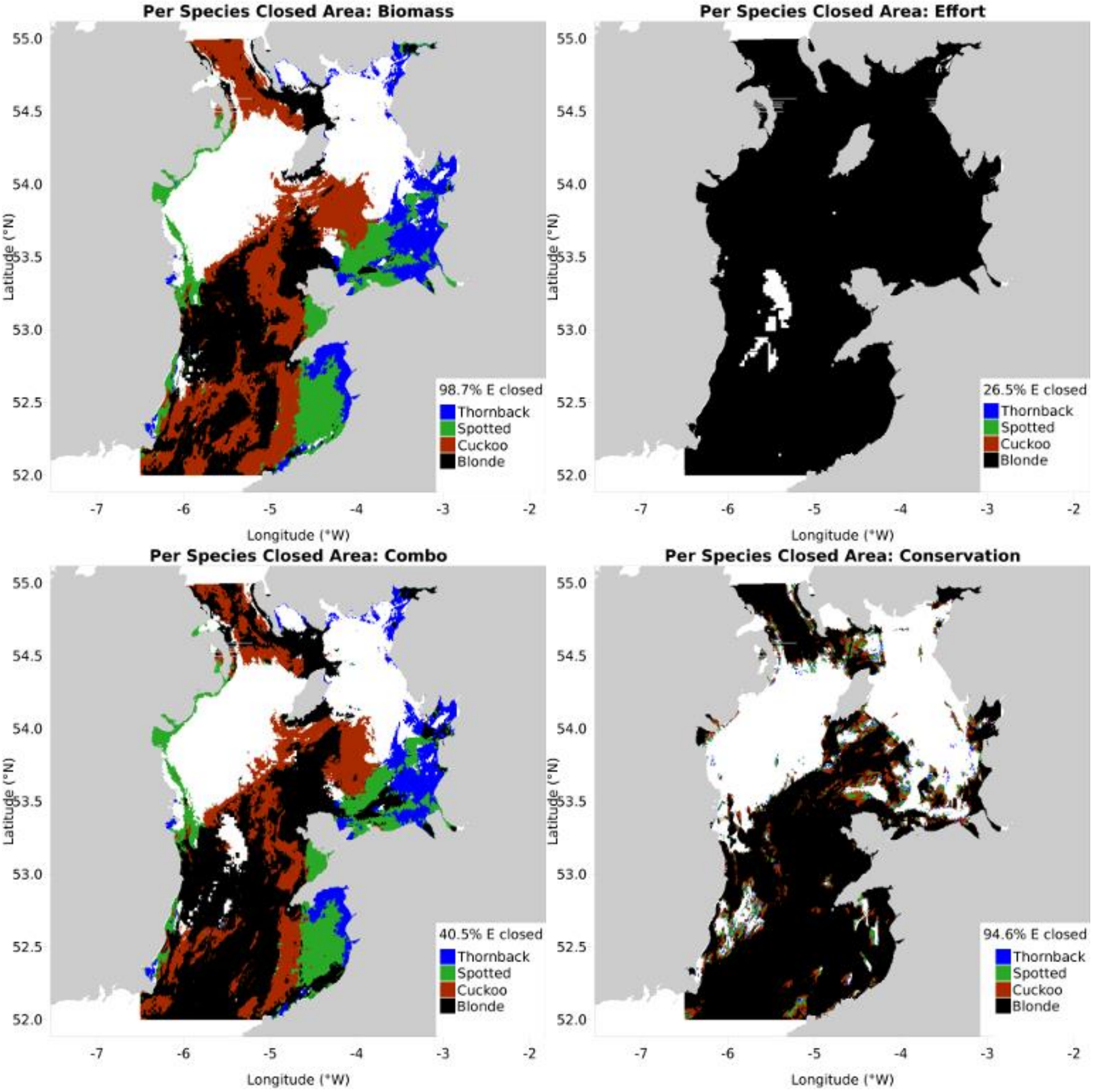

Figure 5: Maps of cumulative closed areas prioritising species biomass, fishing effort, a combination of both, and conservation areas. Areas are successively closed from the most to least vulnerable: blonde ray, cuckoo ray, spotted ray, thornback ray, until each species reaches HR_{MSY}. Legend percentages are the amount of fishing effort displaced

Again with the default 1:1 ratio of ray CPUE to fishing effort, the *cumulative* closed areas produced by the different sorting strategies are displayed in Figure 5, expanding from the most to least vulnerable: blonde ray, cuckoo ray, spotted ray, thornback ray. The Biomass Sort displaces 99% of the fishing effort, as this method places no importance on fishing effort. The Effort Sort displaces 27% of the effort, but closes all of the Irish Sea *except* the effort hotspots. The Combination Sort closes a similar area to the Biomass Sort, but co-prioritises reduction of effort displacement, so the main effort hotspot is largely retained, with only 41% of the effort displaced. The Conservation Sort displaces 95% of the effort and closes much of the Irish Sea. The Biomass, Combination and Conservation Sorts close off a large proportion of the Irish Sea, with the Biomass and Conservation Sorts displacing the main fishing grounds as part of those closures. The Effort Sort basically closes all of the Irish Sea except for the main fishing grounds, including the very low ray productivity areas like the muddy nephrops grounds off 53.5 to 54.5°N off the Irish coast, and in the North Eastern bays.

	Combination	**Biomass**	**Effort**	**Conservation**
Blonde	34.7	94.7	26.5	85.4
Cuckoo	12.4	58.3	3.5	91.7
Spotted	7.3	50.7	1.1	95.2
Thornback	3.2	6.1	0	96
Blonde Cumulative	34.7	94.7	26.5	86.8
Cuckoo Cumulative	39.5	97.7	26.5	91.4
Spotted Cumulative	40	98.2	26.5	93.6
Thornback Cumulative	40.5	98.7	26.5	94.6

Table 3: Fishing effort displaced by the closed areas of different sorting methods (%)

Table 3 shows the percentages that closed areas displace the fishing effort, for different species under different sorting scenarios, both as individual species and cumulative (multiple) species closures. The cumulative scores in the bottom row are the final displacement percentages displayed in the legends in Figure 5. As one might anticipate, the Biomass and Conservation Sorts show high displacement as they focus solely on the rays. Conversely the Effort Sort shows low displacement as it focuses primarily on minimising effort displacement, similar to the effort-weighted Combination Sort (Table 2). The Combination Sort has a displacement a little higher than the Effort Sort but noticeably lower than the Biomass and Conservation sorts.

5 Discussion

5.1 Overview

Managing vulnerable, data-poor elasmobranch species to MSY by 2020 is a challenge that may be addressed using spatial management approaches. We combined modelled CPUE (a proxy for abundance) of four ray species with different vulnerabilities, with average annual fishing effort from the targeting fleet, and per-species HR_{MSY} values. These values are the proportions of each species that can be sustainably harvested annually (Shephard et al., 2015). We built a Decision Support Tool which can allow stakeholders to input different management priorities, which then produces guidance on MPA candidates for management consideration. This approach should help increase stakeholder buy-in, thus improve implementation and compliance, and thus increase the likelihood MPA success (Game et al., 2013; Kelleher, 1999).

5.2 Stakeholder and management requirements

BRT approaches have been demonstrated to identify modelled CPUE hotspots for these rays in this area, based on sparse data (Dedman et al., 2015). However, such hotspots cannot be used directly as MPAs without consideration of the effects on stakeholders, especially the commercial fisheries sector. Two of the key principles of successfully siting MPAs are stakeholder engagement, and avoiding effort displacement and non-compliance (Agardy et al., 2011; Fulton et al., 2015; Kelleher, 1999; Suuronen et al., 2010). Spatial modelling can act as a common ground to catalyse discussions between stakeholders with disparate objectives, to address critical questions, and to distil numerous opinions into a few clear and tractable aims (Fulton et al., 2015). Policymakers need models that integrate science into the management process, increase their available options, and help them identify the option that best meets their needs (Fulton et al., 2015; Pielke, 2007). The BRT modelling plus DST approach developed here addresses the above concerns. In addition, this DST approach will address the problem in fisheries management whereby policymakers often adopt positions they feel will disappoint all parties as little as possible (Pope, 1983).

5.3 MSY underpinning and proxies

Typically managing a stock to MSY would involve calculating its F_{MSY} and using that to calculate a Total Allowable Catch (TAC) limit, based on the Spawning Stock Biomass (SSB), at the appropriate stock-specific spatial scale. However this is not possible in this and many similar cases, either due to a lack of the data required to calculate a species' MSY, or because the management regime doesn't lend itself to single-species TACs. The rays in this case study are mostly caught as bycatch, so applying single-species TACs would increase discarding because the rays would become *choke species* (Schrope, 2010) to fleets primarily targeting other stocks (*i.e.* their TACs would be depleted faster than the target species' TACs, preventing the fleets from any further fishing for the target species, since that would risk illegally catching more rays)(ICES WGEF, 2014). Because of these technical barriers to implementing the traditional MSY approach, ICES has called for fisheries scientists to evaluate MSY *proxies* for stocks such as these (Ellis et al., 2010; ICES WGEF, 2012a, 2012b).

5.4 Sorting methodologies revealing stakeholder viewpoints

The method developed in this paper incorporates MSY via the HR_{MSY} proxy, to calculate the CPUE proportion to protect to conserve the stock. The shape and size of a closed area containing that biomass is not predefined. This allows for genuine stakeholder input into the decision-making process, as MPAs can also be created using weighting factors based on (e.g. ICES WGEF (2014)) spawning and nursery areas, and fishermen's first-hand understanding of the stocks. Recognising that conservation plans are prioritisations is a key aspect in spatial planning (Game et al., 2013). Different priorities can be built into the scenario design, such as giving rays individual vulnerability weightings, and balancing stock conservation against effort displacement minimisation.

The results show that the Effort Sort (Figure 4 and 5) achieved the least effort displacement while satisfying the theoretical HR_{MSY} threshold, but at a cost of the largest closed area (Figure 5 and Table 3). Conversely the Biomass and Conservation Sorts both closed most of the Irish Sea in order to reach the theoretical HR_{MSY} thresholds, with both displacing almost all of the fishing effort as well. The Combination Sort achieved a balance between low effort displacement and closed area size, and allows for individual species vulnerability weightings unlike the other sort types. These weightings are another useful way to introduce compromise between species conservation and effort displacement minimisation, and to trade-off total area closed with effort displaced. One could infer that fishermen would prefer the Effort Sort since it reduces effort displacement and still achieves HR_{MSY}. However, this study only includes the ray-targeting fleet: any detrimental impacts on other fleets or human activities, caused by closing most of the Irish Sea to fishing, are not accounted for. Since MPA setting requires consideration and consultation with *all* affected groups (Kelleher, 1999), it is our belief that the Combination Sort will tend to be the most universally attractive, since it quantifiably balances the priorities of multiple groups. This remains to be tested.

Weighting towards individual ray species or fishing effort changes the candidate closed areas in the resulting map, allowing stakeholders to view the impact of their priority choices. The rationale underpinning the weightings in this study were individual ray species vulnerability ratios (ICES WGEF, 2014) and simple 1:10 / 1:1 / 10:1 ray conservation:effort examples. Although already based upon stock status metrics, these ratios were derived simply to demonstrate the changing outcomes produced under different scenarios: more scientifically defensible, mutually agreed figures would be required for actual operation. Factors like market value could be used here instead of species vulnerability, allowing for the inclusion of other management priorities into the modelling procedure, and thus the resultant MPA candidates.

5.5 Closed area results and siting principles

The individual-species Combination Sort closed areas (e.g. Figure 3) align well with the arbitrary '50% maximum CPUE' closed area suggestion in Figure 8 of Dedman et al. (2015), but cover a notably larger area. As the closed areas in this study are derived from HR_{MSY} calculations rather than an arbitrary cut-off, they are based on solid fisheries science foundations. The closed areas also align well with the peak CPUE 'conservation priority areas' in Figure 6 of Dedman et al. (In Review), but again cover a greater area than just these peaks. The positional similarities across the three studies are unsurprising given all three analyses are underpinned by the same datasets, but the recurrence of these hotspots in the face of additional explanatory variables and different management priorities underlines the reliability and reproducibility of this technique.

5.6 MSY and Spatial Management

This study generated closed area proposals using predicted CPUE maps created by BRT modelling of the full species (Dedman et al., 2015) or subset (Dedman et al., In Review) databases. The base layer could instead be provided by other means, providing the data are in a gridded format. This allows practitioners to use alternative methodologies to derive species abundance predictions, such as generalised linear or additive models (GLMs/GAMs (e.g. De Raedemaecker et al. (2012) and references therein), MaxEnt (Elith et al., 2011; Phillips et al., 2004), or MARXAN and its add-ons (Ball and Possingham, 2003; Watts et al., 2009). Delta log-normal BRTs are the best choice for this case study, however – see Dedman et al. (2015) and Elith et al. (2006) for detailed comparisons and performance metrics.

The closed area proposals generated by this approach advance the work of Dedman et al. (2015) by underpinning them with the established fisheries science principles of escapement and MSY. The resulting fine-scale MPA proposals are in demand (Warton et al., 2015), since small-scale MPAs are the most management relevant (Fulton et al., 2015). Fisheries managers and politicians do still need to be mindful of certain mitigating factors and opportunities before establishing MPAs based on these area proposals, however.

The approach detailed in this paper considers MPA-siting relative to its effects on the displacement of fishing effort for the commercial fisheries sector that targets these stocks (TR1 metier: otter trawl and demersal seine with mesh size ≥100mm), but doesn't yet consider other stakeholders, like other fishery metiers, tourism, wind farms, and so forth. Incorporating these elements could be achieved by factoring in certain areas as pre-set closed areas (like wind farms and buffer zones around them), and summing the losses for the other groups as we currently do for the TR1 metier. This would allow for a more holistic appraisal of the effects of proposed areas closures, and invite representative inclusion of those stakeholder groups.

There is value in assessing whether the underlying BRT CPUE hotspot maps change over time. Inflexibility towards mobile species and climate change is a common failing of closed areas (Fulton et al., 2015), while repeated high CPUE is required to define nursery areas (Heupel et al., 2007). Dedman et al. (2015) pooled the data from all years into a single analysis. Teasing out yearly CPUE hotspot maps (e.g. with bootstrapping) would allow this study's analysis to generate yearly closed area maps, which would then allow the spatial management of these stocks to adapt to changing conditions in an open dialogue with stakeholders. This would of course be facilitated by a richer dataset or with dedicated sampling, but these are luxuries one cannot expect to prescribe, especially for elasmobranchs which are frequently data deficient (Dulvy et al., 2014). Further, creating a high-resolution abundance modelling DST for data-poor species was the aim of this and related studies; the tools are understandably anticipated to work even better with richer underlying data.

5.7 Caveats and further work

Fishing effort was used to model the priorities of the fleet, but CPUE or LPUE (landings per unit effort) may more accurately represent fishermen's spatial preferences, and could be incorporated into future applications of the tool. An alternative to the current algorithmic priority-weighting would be to allow stakeholders to digitally draw their own MPAs, and have the software then calculate and display the proportion of each species' theoretical HR_{MSY} that is protected by that MPA, in real time. The digital maps could be pre-populated with the current algorithm-determined MPAs, with stakeholders then editing them based on their tacit knowledge. It would allow fishermen to factor in steaming time and therefore fuel costs, for example. Incorporating fishermen's knowledge into fisheries management is typically problematic, but highly desirable given the value of such knowledge (Hind, 2012; Johannes, 2003; Johannes et al., 2000; Soto, 2006).

The HR_{MSY} figures were calculated for the adjoining Celtic Sea (ICES area VIIg) by Shephard et al. (2015), and thus may not be perfectly suited to the neighbouring Irish Sea (VIIa). Management utilisation of this approach as an advisory tool may thus require investment in validating the key inputs on HR_{MSY}, vulnerability and harvest ratio.

Dissolved oxygen and chlorophyll were omitted as explanatory variables due to a lack of availability and data processing time constraints. It has been shown that elasmobranchs are sensitive to these variables (Navarro et al., 2016, 2015; Speers-Roesch et al., 2012) so it would be valuable to re-run the analysis with them included.

6 Conclusion

This methodology allows us to map vulnerable ray CPUEs with reference to their habitat, and use this information to develop MSY-proxy spatial closure candidates, based on the principle of conserving an escapement biomass. We were able to build management priorities directly into the mapping process, and then propose closures which can minimise the displacement of effort, which is classic problem in spatial management of fisheries. This method gives fishermen the ability to propose closures based on their own preferences but still underpinned by biological science, and within the remit of the Common Fisheries Policy.

7 Acknowledgements

The authors appreciate the input of Graham Johnston and Sam Shephard's local and biological knowledge, and Hans Gerritsen's statistical and programming expertise. We gratefully acknowledge the critical comments of the reviewers, which helped to improve the present paper.

Research funding was received from the European Community's Seventh Framework Programme (FP7/2007–2013) under grant agreement MYFISH number 289257. David G. Reid also acknowledges funding from a Beaufort Marine Research Award, carried out under the Sea Change Strategy and the Strategy for Science Technology and Innovation (2006–2013), with the support of the Marine Institute, funded under the Marine Research Sub- Programme of the National Development Plan 2007–2013. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

8 Author Contributions

Conceived and designed analyses: SD DGR DB RO MC. Performed analyses: SD. Wrote paper: SD DGR DB RO MC

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10 Supplementary Material

Environmental Dataset	Spatial Resolution	Source
Depth	275x455m grids	EMODnet (European Marine Observation and Data Network)(EMODnet, 2014)
Average Monthly sea bottom temperatures 2010-2012 (°C), Average Monthly sea bottom salinities 2010-2012 (ppm), Maximum monthly 2 dimensional velocity ($m.s^{-1}$)	1185x1680m grids	Marine Institute, 2014 (http://www.marine.ie/Home/site-area/data-services/data-services)
Substrate (grain size in mm)	>= $250m^2$ grids	British Geological Survey, 2011 (British Geological Survey, 2011)
Distance to shore (m)	275x455m grids	via European coastline layer (freely available)

Fishing & Predation Dataset	Spatial Resolution	Source
Surveyed ray CPUE (numbers per hour), 1990-2014	Point data (n=1447)	ICES DATRAS (ICES, 2015)
Surveyed fish predator CPUE (numbers per hour), 1990-2014	Point data	ICES DATRAS (ICES, 2015)
Average annual ray LPUE from demersal trawls (Kg^{-Hr}), 2006-2012	0.02° lat * 0.03° lon grids	Marine Institute, 2014
Average annual whelk LPUE (Kg^{-KwH}), 2009-2013	0.5° lat * 1° lon ICES rectangles	Marine Management Organisation, 2015
Average annual scallop dredging effort (KwH), 2006-2013/2014	0.5° lat * 1° lon ICES rectangles	Marine Management Organisation, and Marine Institute, 2015
Average annual scallop dredging effort (hours), 2006-2014	0.02° lat * 0.03° lon grids	Marine Institute, 2015

Table 4: Datasets used during modelling, and their sources. Ppm: parts per million. Mm: millimetres. $M.s^{-1}$: metres per second. M: metres. CPUE/LPUE: catch/landings per unit effort. Kg: kilogrammes. Hr: hour. KwH: Kilowatt-hour.