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A flexible decision support tool for MSY-based MPA design

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Abstract

ICES WGEF recommends 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 abundance of four ray species (cuckoo, thornback, blonde, and spotted), created using Boosted Regression Tree modelling. We then use a Decision Support Tool to generate location and size options for MPAs 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. The result is a complete software package that produces maps of predicted species abundance 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
- 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., 2005; 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 (Commission, 2013). Spatial management tools explored by ICES WGEF (2012a) have been further developed (Dedman et al., 2015, in review) 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). BRTs 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), and 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).

TABLE 1 LOCATION

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 (*escapement biomass*).

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 negative consequences on the stocks (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). We combine this 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 minimizing disruption to fishing activity and the displacement of effort, under a range of exploitation and conservation scenarios. We 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 LOCATION

The predicted CPUE maps used as inputs were generated using the delta log-normalised BRT-predicted CPUE mapping approach developed and 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) and ray CPUE from 1447 fishery-independent survey sites (ICES, 2013) then predicts ray CPUE to the remainder of the Irish Sea based on the environmental variable values there.

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 per Dedman et al. (2015), and juvenile ray and eggcase reducing variables (predatory fish CPUE, fishing effort, scallop dredging effort, whelk CPUE).

For the closed area modelling, the BRT-predicted CPUE maps were scaled to 1, and multiplied by per-species weighting factors if required. These weighting factors allow for the manipulation of the relative importance of fishing and conservation and the conservation weightings for each species can be set individually. To compare outcomes under different management strategies we tested four different conservation:fishing weighting scenarios. These were:

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

And finally, to investigate the consequences of differing species conservation priority we applied species-specific vulnerability weightings. These were derived from ICES WFEG (2014) conservation status metrics, with negative elements being given a score of 1, and benign elements 0. The elements were fishing pressure, stock size, and percent of spawning in study area. There 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 all 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.

Fishing effort was expressed on an inverted scale from 0 for maximum effort, to 1 for no effort. It was then added to the CPUEs, creating a Combination Metric running from 0 (0 CPUE and maximum effort) to 2 (maximum CPUE and no effort). 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.

To evaluate alternative management priorities, species data were subsequently sorted according to:

- Combination Sort: sorting by the aforementioned Combination Metric, high to low;

- Biomass Sort: sorting by CPUE, high to low; emphasising protecting areas on a high biomass basis only
- Effort Sort: sorting the fishing effort data, low to high; emphasising protecting areas on a low fishing effort basis only
- Conservation Sort: sorting the conservation data, high to low; emphasising protecting areas on a high conservation basis only
- 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.

To ensure that candidate protected areas contain the escapement biomass, the model then sums the biomass until the cumulative total of biomass reaches the HR_{MSY} proportion of that species' total biomass. These are then considered as the candidate closed areas, which are then mapped, on top of the Combination Metric background. Displaced effort is calculated as the effort in the closed area, and expressed as a percentage of total effort.

For each sort type cumulative closed area maps are then calculated, starting with the most vulnerable species. This initial closed area is then extended using the same approach, until the *second* most vulnerable species' B*pa* is reached. The process is repeated sequentially for all species in order of their vulnerability. In some cases a species' B*pa* may already be reached by the cumulative closed area calculated for the previous species. In this study, the B*pa* is a theoretical concept, because we only consider a subset of the extent of the four ray stocks.

4 Results

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

FIGURE 2 LOCATION

FIGURE 3 LOCATION

Altering the rays: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; centre panel of Figure 3). Giving the rays a weighting of 10 (10:1 ratio, left panel) shifts some of the area closure onto areas of fishing effort, resulting in a total displaced effort of 38.4%. Prioritising effort (1:10 ratio, right panel) results in a 3.3% displaced effort, with the closed area avoiding sites of even low effort thus expanding across a greater area of moderate ray CPUE.

TABLE 2 LOCATION

Table 2 shows the percentages of fishing effort that closed areas displace with under different weighting scenarios, all under the Combination Sort scenario. These are given for individual species and cumulative (multiple) species area closures. Weighting in favour of rays (bottom row of columns three and four) understandably 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, columns 2 and 1). One can see the effect of the weighting process when comparing the individual-species closed area displacements (top four rows) for the 1:1 ray scores (column one) to the per-species weightings (column four): blonde and cuckoo ray have weightings of 4.17 and 3.5 respectively (column four header), which sees their closure displacements rise 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.

FIGURE 4 LOCATION

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 (Figure 4, top left panel) 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 (Figure 4, top right panel) displaces only 4% of the effort, but closes a larger area. The Combination Sort (Figure 4, bottom left panel) displaces 12% of the effort while still closing a very similar area to the Biomass sort. The Conservation Sort (Figure 4, bottom right panel) displaces 92% of the effort and closes much of the Irish Sea.

FIGURE 5 LOCATION

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 (black), cuckoo ray (red), spotted ray (green), thornback ray (blue). The Biomass Sort (Figure 5, top left panel) displaces 99% of the fishing effort, as this method places no importance on fishing effort. The Effort Sort (Figure 5, top right panel) displaces 27% of the effort, but closes all of the Irish Sea *except* the effort hotspots. The Combination Sort (Figure 5, bottom left panel) displaces 41% of the effort while still closing a similar area to the Biomass Sort, although obviously it prioritises reducing effort displacement as well, so the main effort hotspot is largely uncovered. The Conservation Sort (Figure 5, bottom right panel) 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 closes basically 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.

TABLE 3 LOCATION

Table 3 shows the percentages that closed areas displace 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 align with the final displacement percentages displayed in the legends in Figure 5. As one might anticipate, the Biomass and Conservation Sorts (columns two and four) have high displacement as they focus solely on the rays. Conversely the Effort Sort (column three) has low displacement as it focuses primarily on minimising effort displacement, similar to the effort-weighted Combination Sort (column two in Table 2). The Combination Sort (column 1 in Table 2) 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 – as a proxy for abundance – of four differentially vulnerable ray species with average annual fishing effort from the fleet targeting those rays, and per-species HR_{MSY} values. This produced a DST which allows stakeholders to evaluate the MPAs resulting from a range of management priorities. This approach should help increase stakeholder buy-in with the beneficial consequences for implementation and compliance, and thus increase the likelihood of success of the MPA.

5.2 Stakeholders and management

BRT approaches have been demonstrated to identify modelled CPUE hotspots for these rays in this area, based on sparse data (Dedman et al., 2015, in review), but these results cannot support area closures such as MPAs without considering their likely effects on other stakeholders, especially the commercial fisheries sector. Some 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, address critical questions, and 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).

This DST approach could be used to address the problem in fisheries management whereby policymakers often adopt positions they feel will disappoint all parties as little as possible (Pope, 1983). 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 latest (Commission, 2013).

5.3 MSY underpinning and proxies

Typically this would involve calculating the F_{MSY} then using that figure to calculate a Total Allowable Catch (TAC) limit, based on the SSB, for a targeted single species, at the appropriate stock-specific spatial scale. However in this and many similar cases this is not possible 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. In this case study, this is because these rays are mostly caught as bycatch, and 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 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 the principle of MSY, using the HR_{MSY} proxy, in order to generate a biomass that must be protected in order to conserve the stock – but the shape and size of the closed area chosen to reach that biomass is not predefined. This allows for genuine stakeholder input into the decision-making process, whereby MPAs can be drawn up based on weighting factors agreed between scientists, based on e.g. ICES WGEF (2014) spawning and nursery areas extents, and fishermen, based on their 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 individually weighting the rays based on their respective vulnerabilities, and balancing stock conservation against effort displacement minimisation. The results show that the Effort Sort (top right panel, Figure 4 and 5) achieved the least effort displacement while satisfying the theoretical B*pa* threshold, but at a cost of the largest closed area (Figure 5 and Table 3). The Combination Sort (bottom left panel, Figure 4 and 5) achieved a balance between low effort displacement and closed area size, and is also beneficial since it allows for individual species vulnerability weightings, which are nullified in the other sorting techniques. The Biomass and Conservation Sorts (top left and bottom right panels respectively, Figure 4 and 5) both closed most of the Irish Sea in order to reach a theoretical B*pa* threshold, with both displacing almost all of the fishing effort as well.

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

5.5 Closed area results and siting principles

The individual-species Combination Sort closed areas (e.g. central panel, 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. The closed areas in this study are derived from HR_{MSY} calculations rather than an arbitrary cut-off, however, meaning that they are more reliably based on solid fisheries science foundations. They 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 not especially surprising since all three analyses are underpinned by the same datasets.

5.6 MSY and Spatial Management

This study suggests candidate closed areas 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 also be provided by other means, as long as the data are in a simple gridded format. This gives one scope 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) for detailed comparisons and Elith et al. (2006) for comparative performance metrics.

The closed area proposals generated by this approach advance the work of Dedman et al. (2015, in review) by underpinning them with the established fisheries science principles of escapement and MSY. This results in fine-scale MPA proposals which are much in demand (Warton et al., 2015), as 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 (TR1 metier: otter trawl and demersal seine with mesh size ≥100mm) that targets these stocks, 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.

We have framed the outputs of this study as leading to permanent MPAs – but this does not necessarily need to be the case. Building on underlying maps of the CPUEs of juvenile and adult female subsets, using the methodology of Dedman et al. (in review), areas could be closed temporarily, based around each species' reproductive cycle. This could be paired with technical/gear measures, such that all ray fishing could be banned from juvenile hotspots, minimum landings sizes could be in place year-round, and maximum landing sizes could be in place within mature female hotspots during spawning seasons, for example.

There is value in assessing how the underlying BRT abundance hotspot maps change on a yearly basis. Inflexibility in the face of mobile species and climate change is a common failing of closed areas (Fulton et al., 2015), and repeated high CPUE is a required condition to satisfy the definition of a nursery area (Heupel et al., 2007). Dedman et al. (2015) pooled the data from all years into a single analysis. Teasing out yearly hotspot maps (e.g. with bootstrapping) could produce yearly closed area maps which would allow the spatial management of these stocks to continually adapt to the changing situation, in a yearly open dialogue with all stakeholders.

5.7 Caveats and further work

Fishing effort was the metric used to model the priorities of the fleet, but CPUE or LPUE (landings per unit effort) may more accurately represent their spatial references and could be incorporated into future applications of the tool. The current approach allows many differing preferences to be incorporated, but it is still prescriptive, insofar as it uses a set algorithm. An alternative would be to build a feature on top of the *Bpa* summing process that would allow stakeholders to draw their own MPAs onto a digital map, and see what proportion of each species' theoretical *Bpa* is protected by the MPA, in real time. These could be based in greater or lesser degree on the algorithm determined candidate areas, and could draw on stakeholders tacit knowledge. It would allow fishermen to factor in steaming time and therefore fuel costs, for example.

The Harvest Rate figures from Shephard et al. (2015) were calculated for the adjoining Celtic Sea (ICES area VIIg), and thus may not be perfectly suited to the 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.

6 Conclusion

This methodology allows us to map vulnerable ray CPUEs with reference to their habitat, and use this information to develop MSY-proxy candidate spatially closures, based on the principle of conserving an escapement biomass. We are able to build management priorities directly into the mapping process, and then propose closures which can minimise the displacement of effort, which is the 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.

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8 Author Contributions

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

9 References

Agardy, T., Di Sciara, G.N., Christie, P., 2011. Mind the gap: Addressing the shortcomings of marine protected areas through large scale marine spatial planning. Marine Policy 35, 226–232.

Ball, I.R., Possingham, H.P., 2003. MARXAN - A Reserve System Selection Tool [WWW Document]. URL http://www.ecology.uq.edu.au/marxan.htm (accessed 13–6.13).

Baum, J.K., Myers, R.A., Kehler, D.G., Worm, B., Harley, S.J., Doherty, P.A., 2003. Collapse and conservation of shark populations in the Northwest Atlantic. Science 299, 389–392.

Brander, K., 1981. Disappearance of common skate Raia batis from Irish Sea. Nature 290, 48 – 49. doi:10.1038/290048a0

Commission, E., 2013. No. 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC. Official Journal of the European Union 354, 22–61.

Dedman, S., Officer, R., Brophy, D., Clarke, M., Reid, D.G., 2015. Modelling abundance hotspots for data-poor Irish Sea rays. Ecological Modelling 312, 77–90. doi:10.1016/j.ecolmodel.2015.05.010

Dedman, S., Officer, R., Brophy, D., Clarke, M., Reid, D.G., in review Advanced spatial modelling to inform management of data-poor juvenile and adult female rays. 39pp.

Elith, J., Graham, C.H., Anderson, R.P., Dudı, M., Ferrier, S., Guisan, A., Hijmans, R.J., Huettmann, F., Leathwick, J.R., Lehmann, A., Li, J., Lohmann, L.G., Loiselle, B.A., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., Overton, J.M., Peterson, A.T.P.S.J., Richardson, K., Scachetti-Pereira, R., Schapire, R.E., Soberon, J., Williams, S., Wisz, M.S., Zimmermann, N.E., H Graham, C., P Anderson, R., Dudík, M., J Hijmans, R., R Leathwick, J., G Lohmann, L., A Loiselle, B., McC M Overton, J., Townsend Peterson, A., J Phillips, S., E Schapire, R., Soberón, J., S Wisz, M., E Zimmermann, N., 2006. Novel methods improve prediction of species' distributions from occurrence data. Ecography, Fifty-fifth session 29, 129–151. doi:10.1111/j.2006.0906-7590.04596.x

Elith, J., Phillips, S.J., Hastie, T., Dudík, M., Chee, Y.E., Yates, C.J., 2011. A statistical explanation of MaxEnt for ecologists. Diversity and Distributions 17, 43–57.

Ellis, J.R., Dulvy, N.K., Jennings, S., Parker-Humphreys, M., Rogers, S.I., 2005. Assessing the status of demersal elasmobranchs in UK waters: a review. Journal of the Marine Biological Association of the UK 85, 1025–1048.

Ellis, J.R., Silva, J.F., McCully, S.R., Evans, M., Catchpole, T., 2010. UK fisheries for skates (Rajidae): History and development of the fishery, recent management actions and survivorship of discards. ICES.

Foley, M.M., Halpern, B.S., Micheli, F., Armsby, M.H., Caldwell, M.R., Crain, C.M., Prahler, E., Rohr, N., Sivas, D., Beck, M.W., Carr, M.H., Crowder, L.B., Duffy, J.E., Hacker, S.D., McLeod, K.J., Palumbi, S.R., Peterson, C.H., Regan, H.M., Ruckelshaus, M.H., Sandifer, P.A., Steneck, R.S., 2010. Guiding ecological principles for marine spatial planning. Marine Policy 34, 955–966.

Fulton, E.A., Bax, N.J., Bustamante, R.H., Dambacher, J.M., Dichmont, C., Dunstan, P.K., Hayes, K.R., Hobday, A.J., Pitcher, R., Plagányi, É.E., others, 2015. Modelling marine protected areas: insights and hurdles. Phil. Trans. R. Soc. B 370, 20140278.

Game, E.T., Kareiva, P., Possingham, H.P., 2013. Six common mistakes in conservation priority setting. Conservation Biology 27, 480–485.

Heupel, M.R., Carlson, J.K., Simpfendorfer, C.A., 2007. Shark nursery areas: concepts, definition, characterization and assumptions. Marine Ecology Progress Series 337, 287–297.

ICES, 2013. ICES Database of Trawl Surveys, IBTS VIIa & IGFS Ireland 2003-12 [WWW Document]. URL http://datras.ices.dk (accessed 21–1.13).

ICES WGEF, 2012a. ICES advice: Rays and skates in Subarea VI and Divisions VIIa–c, e–j (Celtic Sea and west of Scotland).

ICES WGEF, 2012b. ICES WGEF Report.

ICES WGEF, 2014. Report of the Working Group on Elasmobranch Fishes (WGEF), 2014. Lisbon, Portugal.

Kaplan, I.C., Levin, P., 2009. Ecosystem-based management of what? An emerging approach for balancing conflicting objectives in marine resource management, in: The Future of Fisheries Science in North America. Springer, pp. 77–95.

Kelleher, G., 1999. Guidelines for Marine Protected Areas. IUCN, Cambridge, UK.

Klein, C.J., Tulloch, V.J., Halpern, B.S., Selkoe, K.A., Watts, M.E., Steinback, C., Scholz, A., Possingham, H.P., 2013. Tradeoffs in marine reserve design: habitat condition, representation, and socioeconomic costs. Conservation Letters 6, 324–332.

Levin, P.S., Kaplan, I., Grober-Dunsmore, R., Chittaro, P.M., Oyamada, S., Andrews, K., Mangel, M., 2009. A framework for assessing the biodiversity and fishery aspects of marine reserves. Journal of applied ecology 46, 735–742.

Penn, J.W., Fletcher, W.J., 2010. The efficacy of sanctuary areas for the management of fish stocks and biodiversity in WA waters, Fisheries Research Report. Government of Western Australia Department of Fisheries.

Phillips, S.J., Dudík, M., Schapire, R.E., 2004. A Maximum Entropy Approach to Species Distribution Modeling, in: Proceedings of the Twenty-First International Conference on Machine Learning. pp. 655–662.

Pielke, R.A., 2007. The honest broker: making sense of science in policy and politics. Cambridge Univ Press.

Pope, J., 1983. Fisheries resource management theory and practice, in: Taylor JL, Baird GG (Ed.), New Zealand Finfish Fisheries: The Resources and Their Management. Trade Publications Limited, Auckland, New Zealand, pp. 56–62.

De Raedemaecker, F., Brophy, D., O’Connor, I., Comerford, S., 2012. Habitat characteristics promoting high density and condition of juvenile flatfish at nursery grounds on the west coast of Ireland. Journal of Sea Research 73, 7–17.

Rogers, S., Ellis, J.R., 2000. Changes in the demersal fish assemblages of British coastal waters during the 20th century. ICES Journal of Marine Science 57, 866–881.

Schrope, M., 2010. Fisheries: What's the catch? Nature 465, 540–542.

Shephard, S., Reid, D.G., Gerritsen, H.G., Farnsworth, K.D., 2015. Estimating biomass, fishing mortality, and "total allowable discards" for surveyed non-target fish. ICES Journal of Marine Science 72, 458–466.

Suuronen, P., Jounela, P., Tschernij, V., 2010. Fishermen responses on marine protected areas in the Baltic cod fishery. Marine Policy 34, 237–243.

Walker, P., Hislop, J., 1998. Sensitive skates or resilient rays? Spatial and temporal shifts in ray species composition in the central and north-western North Sea between 1930 and the present day. ICES Journal of Marine Science 55, 392–402.

Warton, D.I., Foster, S.D., De'ath, G., Stoklosa, J., Dunstan, P.K., 2015. Model-based thinking for community ecology. Plant Ecology 216, 669–682.

Watts, M.E., Ball, I.R., Stewart, R.S., Klein, C.J., Wilson, K., Steinback, C., Lourival, R., Kircher, L., Possingham, H.P., 2009. Marxan with Zones: software for optimal conservation based land-and sea-use zoning. Environmental Modelling & Software 24, 1513–1521.

Worm, B., Davis, B., Kettemer, L., Ward-Paige, C.A., Chapman, D., Heithaus, M.R., Kessel, S.T., Gruber, S.H., 2013. Global catches, exploitation rates, and rebuilding options for sharks. Marine Policy 40, 194–204.

Zabel, R.W., Harvey, C.J., Katz, S.L., Good, T.P., Levin, P.S., 2003. Ecologically sustainable yield. American Scientist 91, 150–157.

Zhou, S., Yin, S., Thorson, J.T., Smith, A.D.M., Fuller, M., Walters, C.J., 2012. Linking fishing mortality reference points to life history traits: an empirical study. Canadian Journal of Fisheries and Aquatic Sciences 69, 1292–1301.

R functions used

gbm.auto, including gbm.map, gbm.rsb, gbm.cons and gbm.valuemap, written by SD

2012-2016 and available at: https://github.com/SimonDedman/gbm.auto

10 Figures and Tables

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

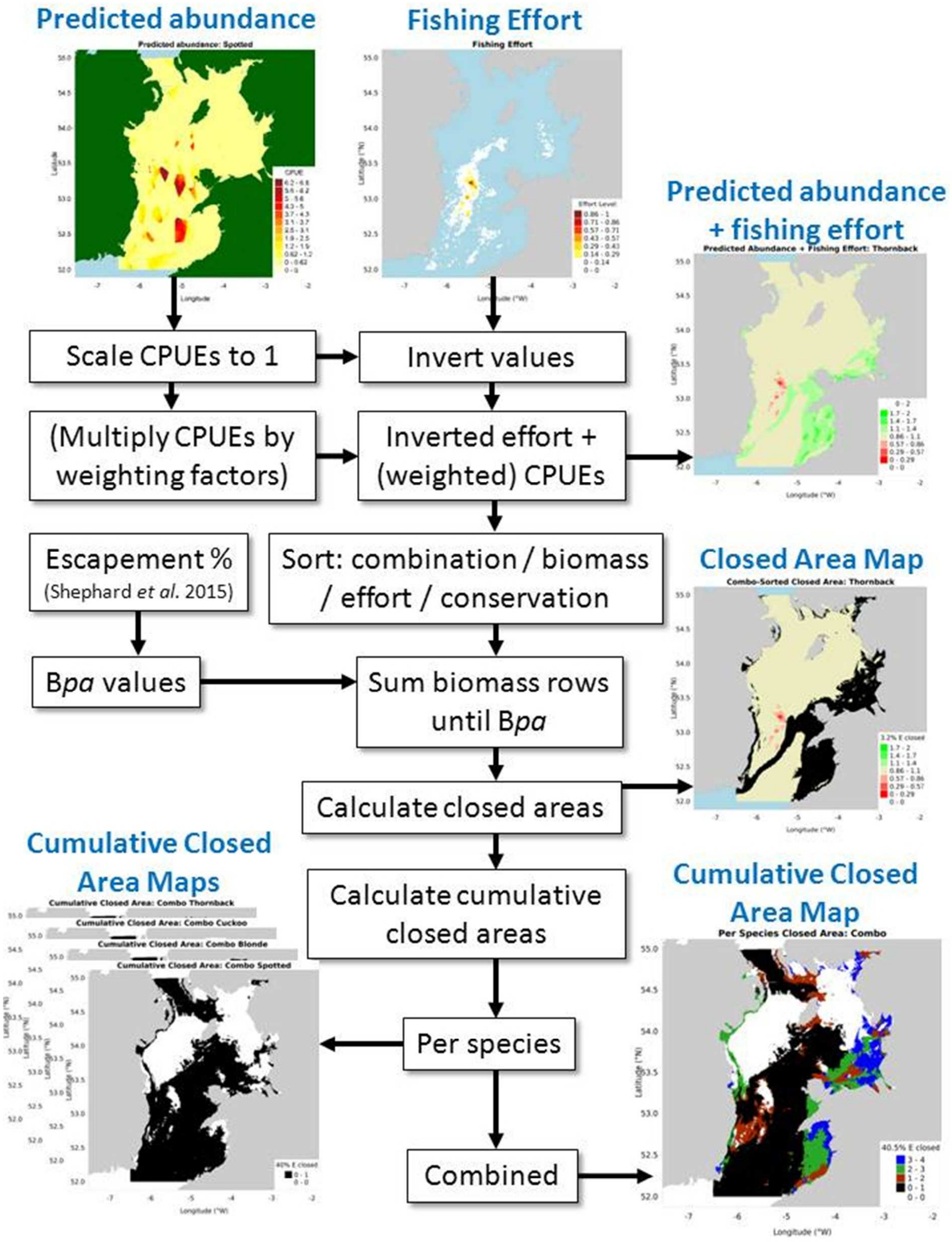


Figure 1: Conceptual diagram of B*pa* closed area approach

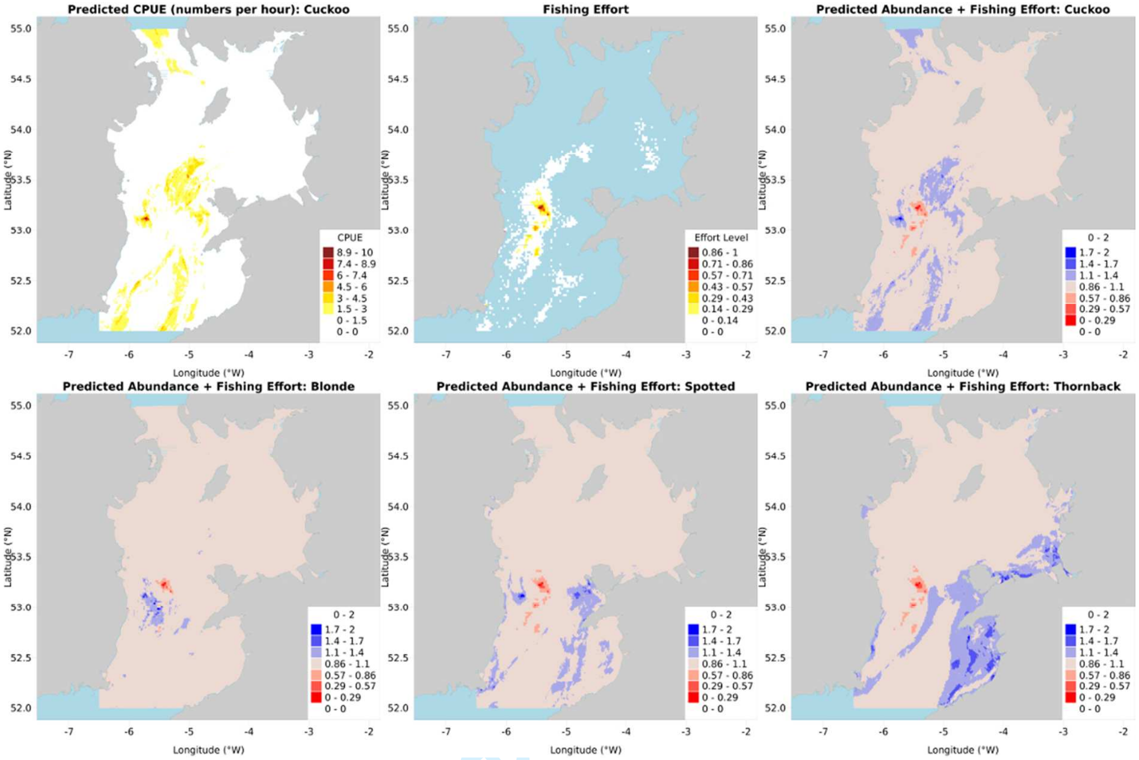


Figure 2: Maps of modelled CPUE then fishing effort for cuckoo ray, and CPUE plus inverted fishing effort both scaled to 1 (blue areas are good to close, red are bad) for cuckoo, blonde, spotted and thornback ray

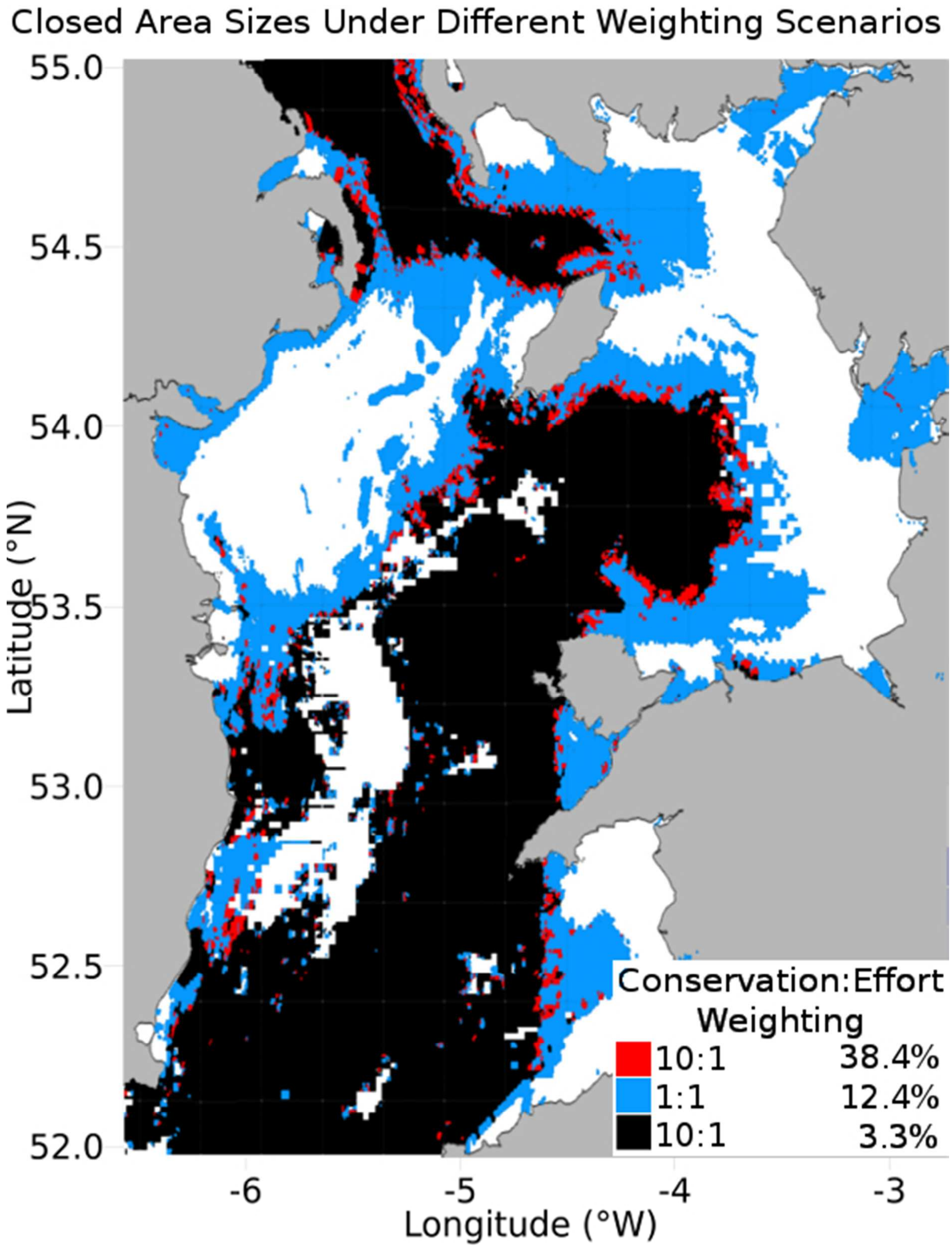


Figure 3: Maps of cuckoo ray closed areas prioritising combinations of conservation and fishing effort, with conservation:effort weightings of 10:1, 1:1 and 1:10

	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

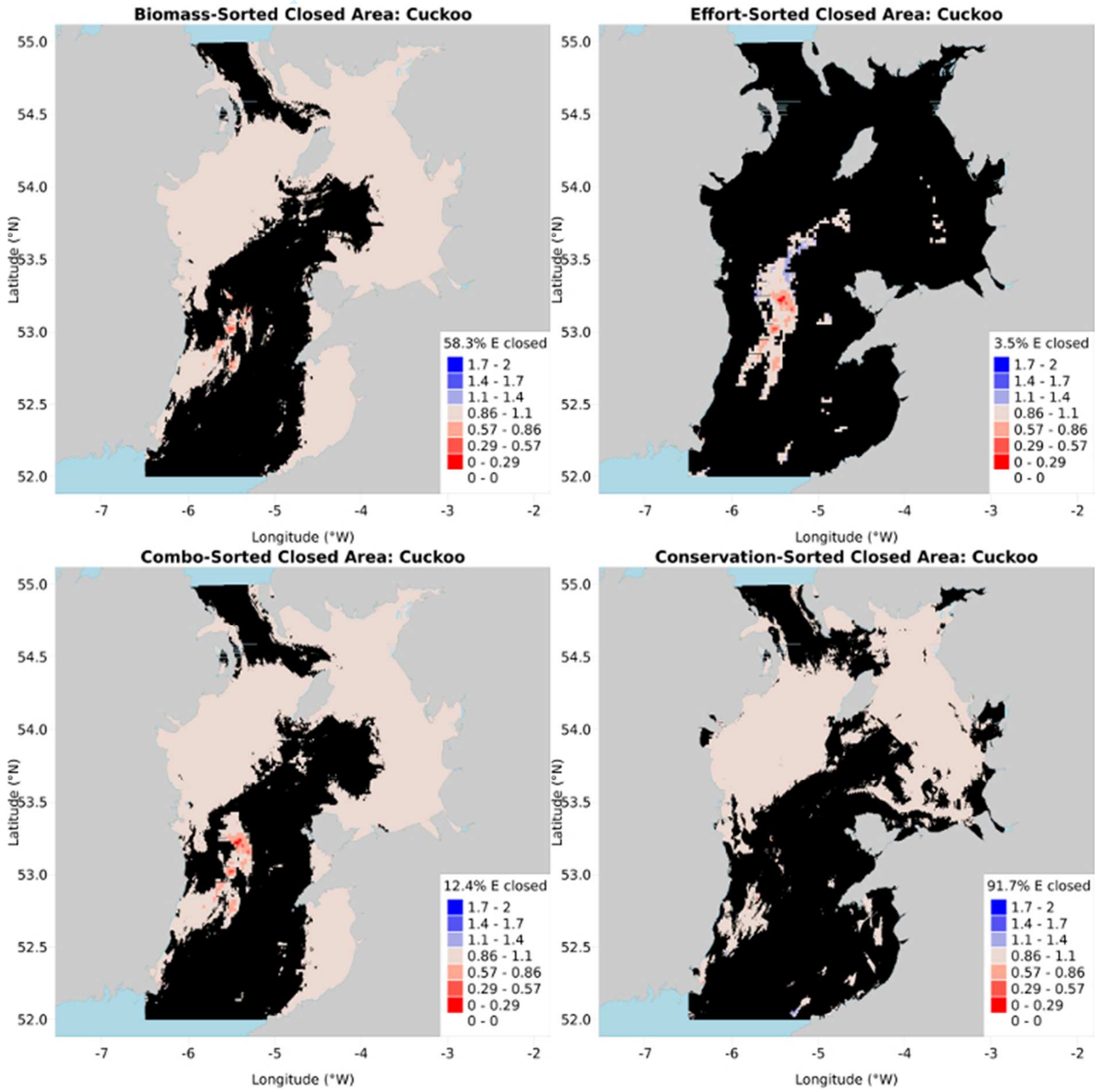


Figure 4: Maps of cuckoo ray closed areas prioritising species biomass, fishing effort, a combination of both, and conservation areas

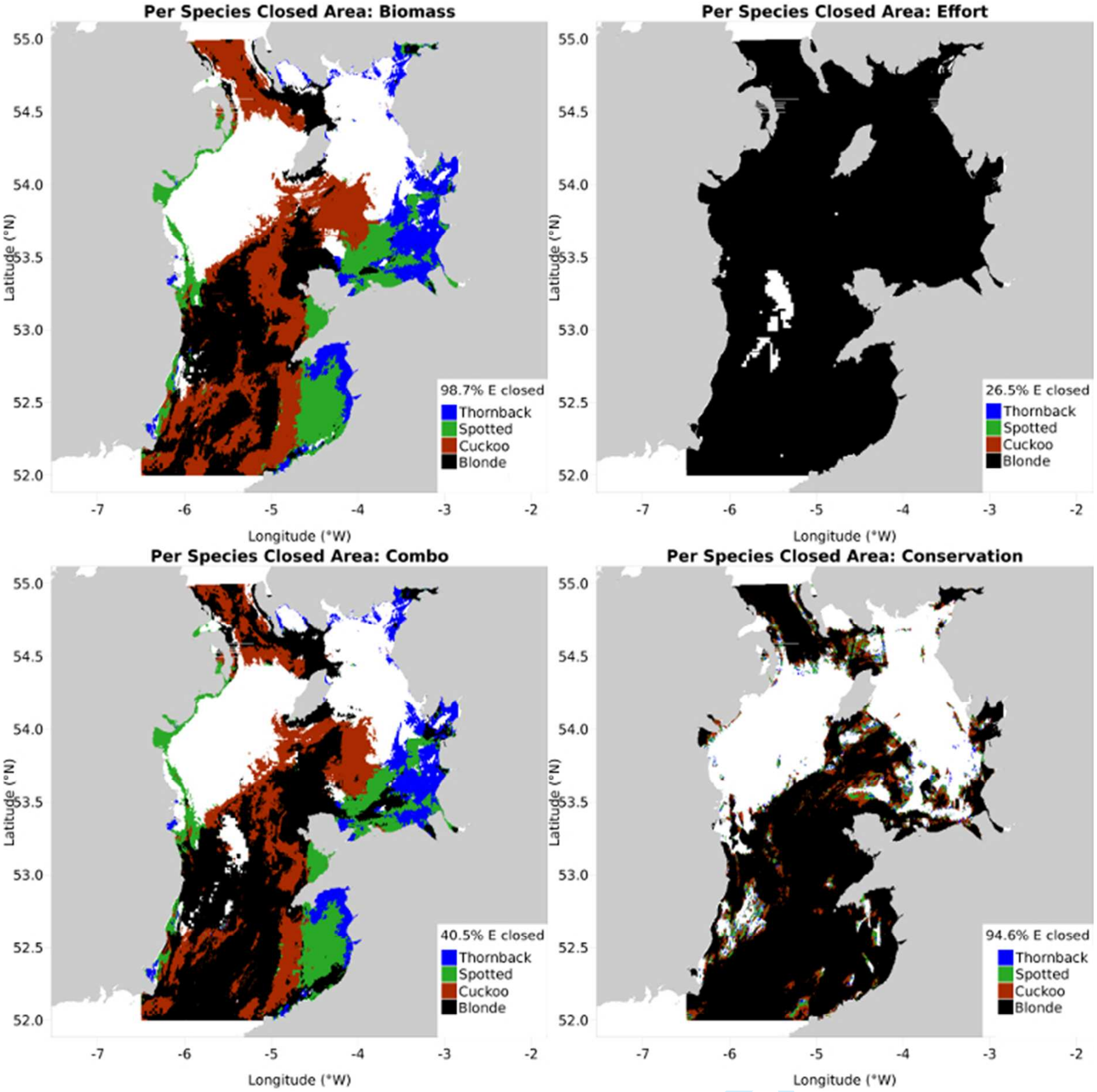


Figure 5: Maps of cumulative closed areas prioritising species biomass, fishing effort, a combination of both, and conservation areas. Areas are successively closed from the most to least vulnerable: cuckoo ray (black), blonde ray (red), spotted ray (green), thornback ray (blue) until each species reaches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

	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 (%)

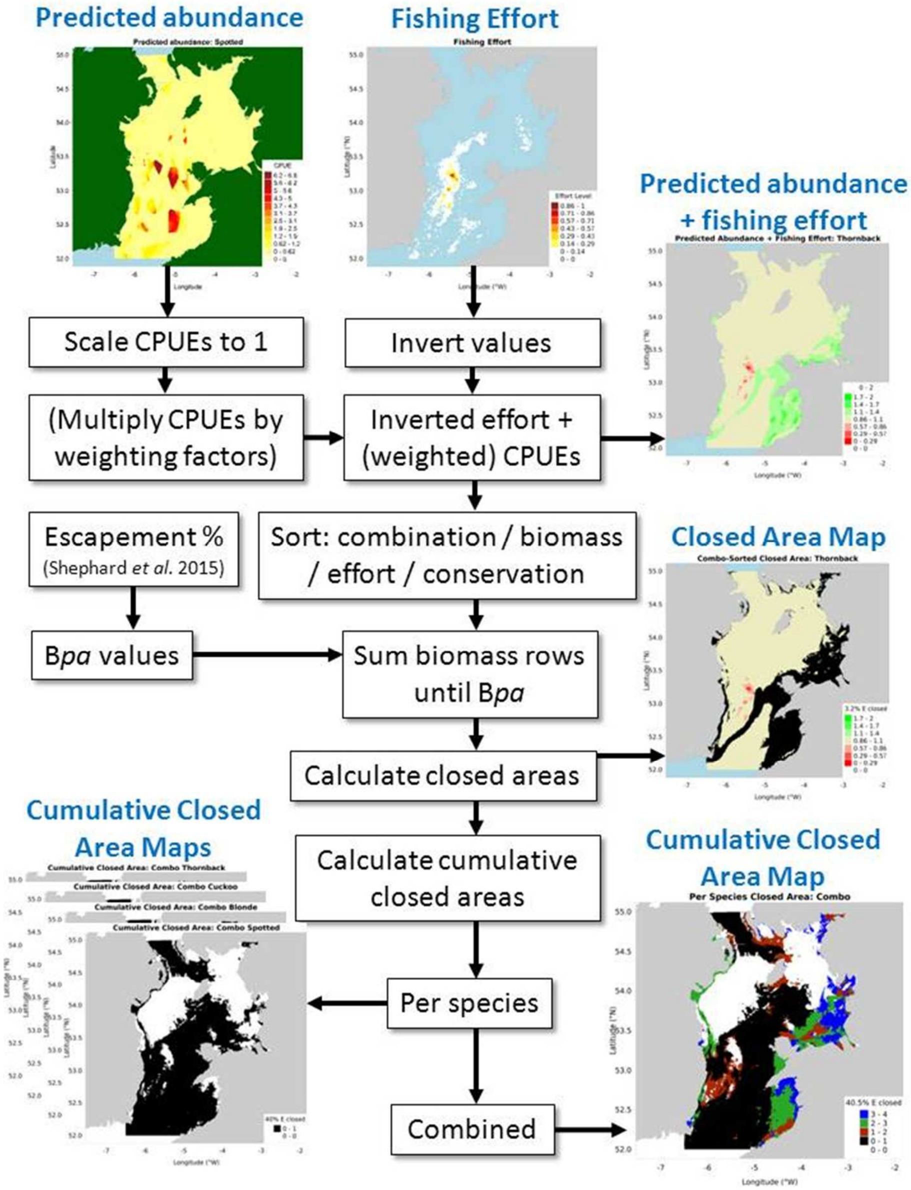


Figure 1: Conceptual diagram of Bpa closed area approach
188x248mm (96 x 96 DPI)

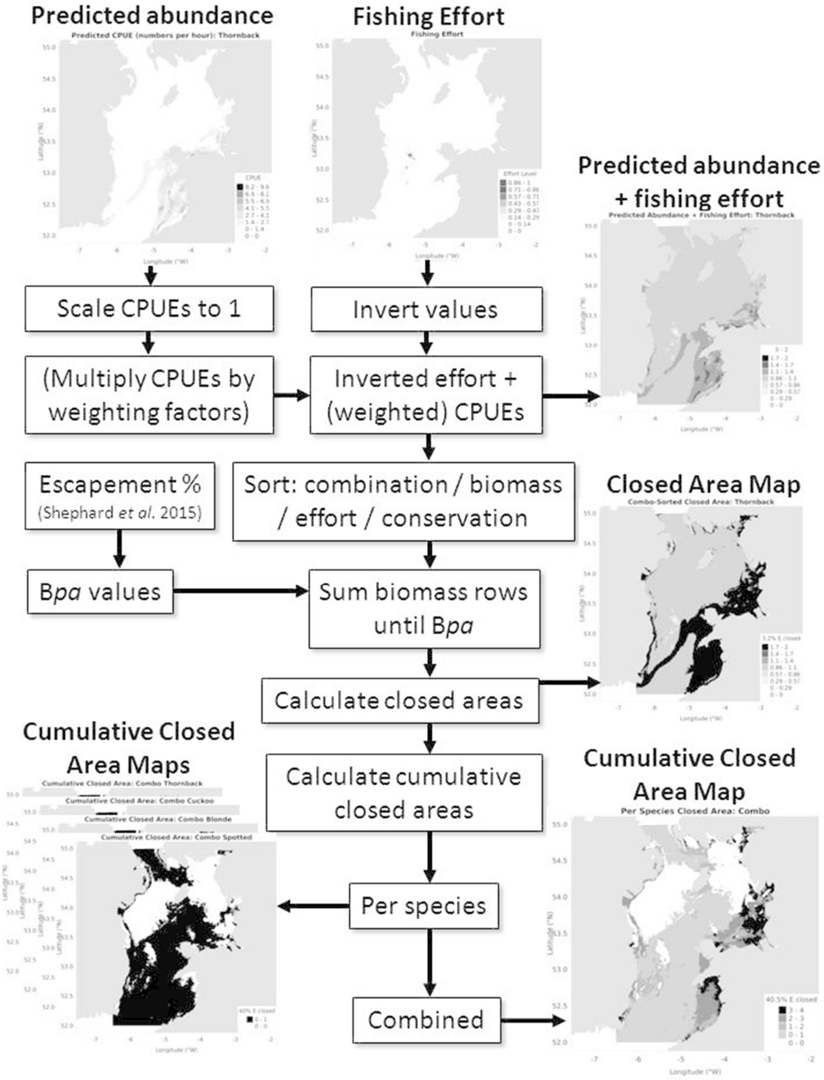


Figure 1: Conceptual diagram of Bpa closed area approach
190x275mm (96 x 96 DPI)

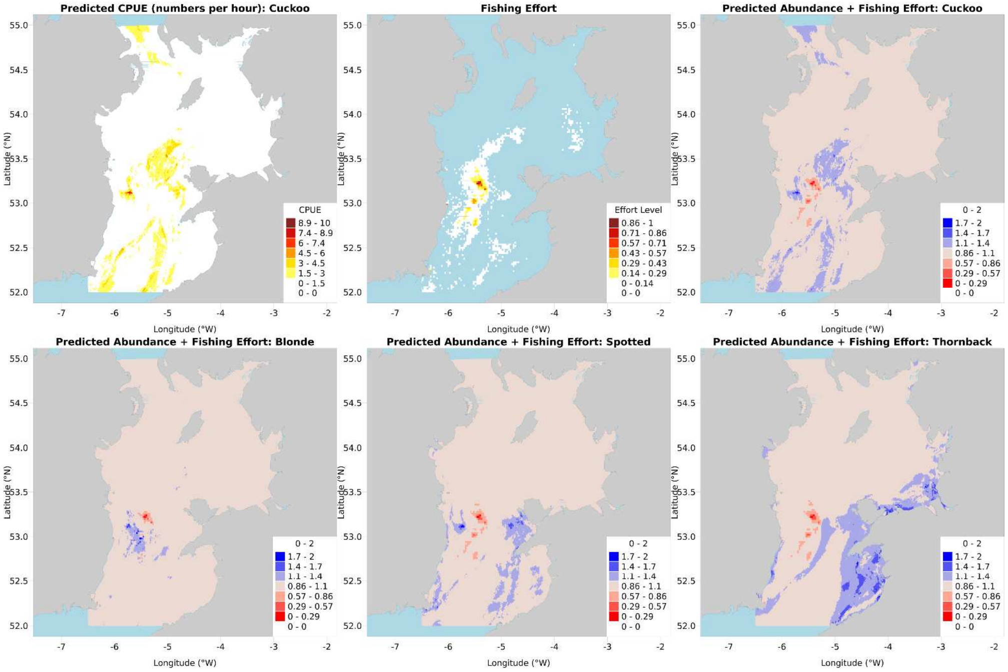
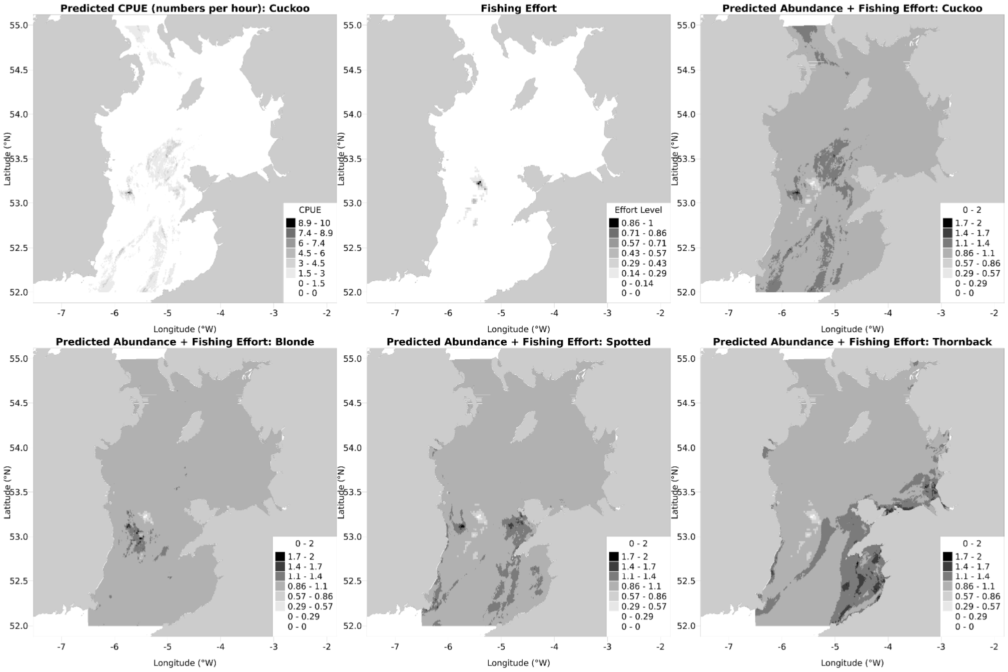


Figure 2: Maps of modelled CPUE then fishing effort for cuckoo ray, and CPUE plus inverted fishing effort both scaled to 1 (blue areas are good to close, red are bad) for cuckoo, blonde, spotted and thornback ray
2731x1821mm (72 x 72 DPI)



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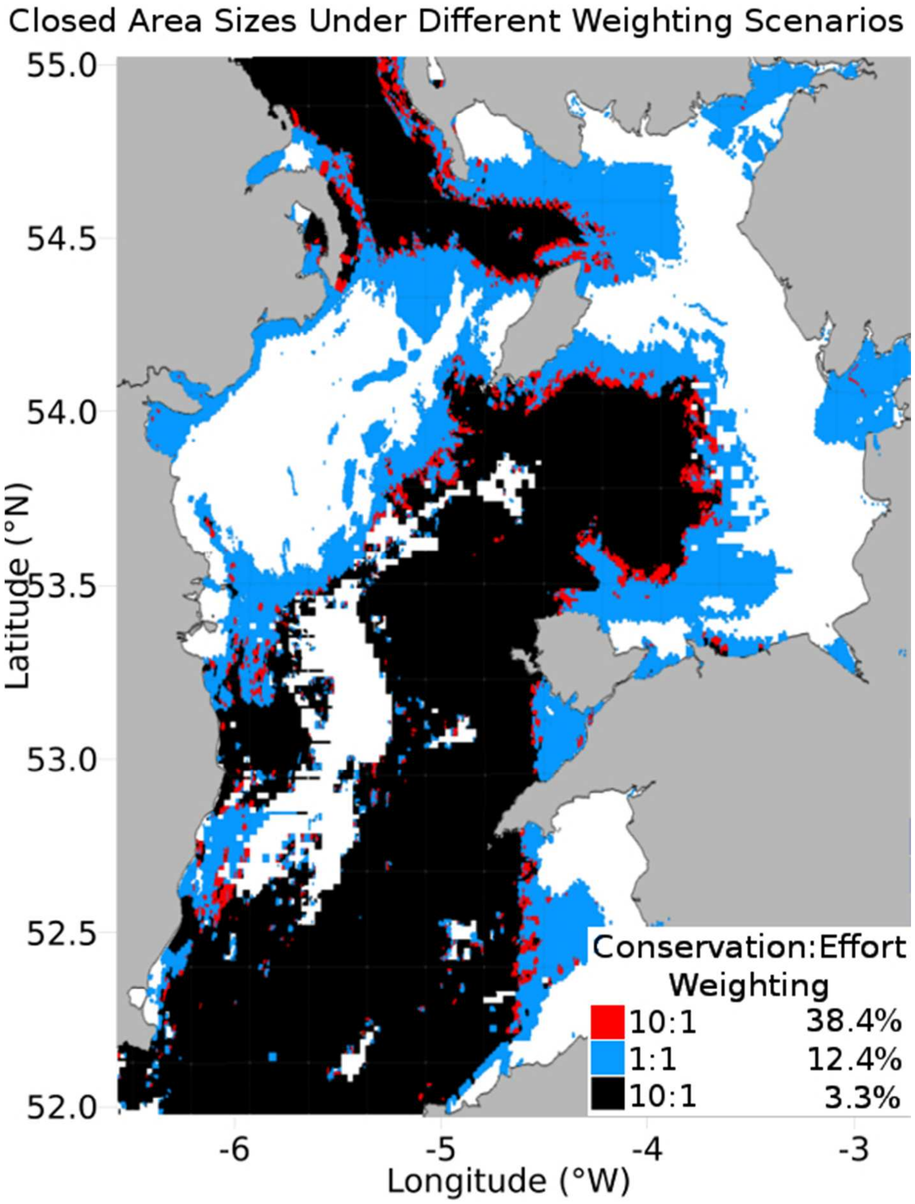
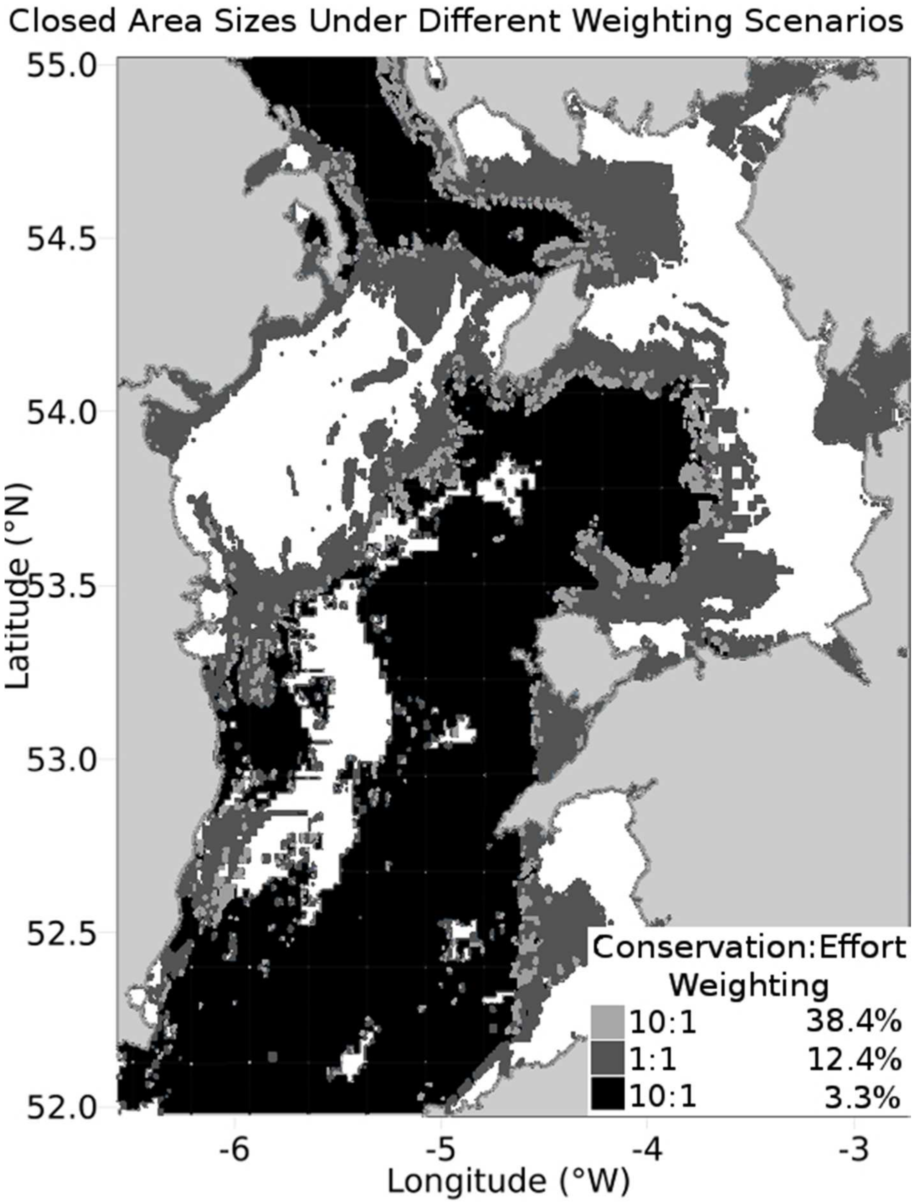


Figure 3: Maps of cuckoo ray closed areas prioritising combinations of conservation and fishing effort, with conservation:effort weightings of 10:1, 1:1 and 1:10
208x275mm (72 x 72 DPI)



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208x275mm (72 x 72 DPI)

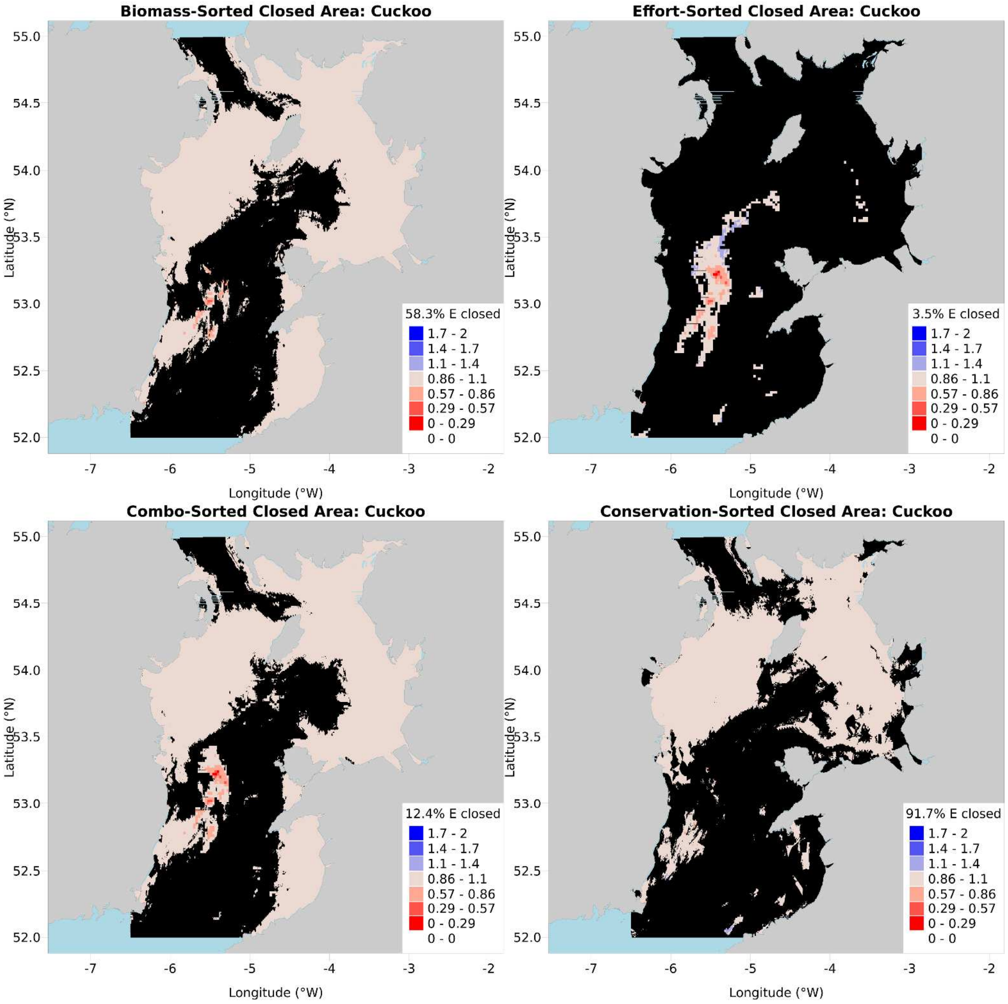
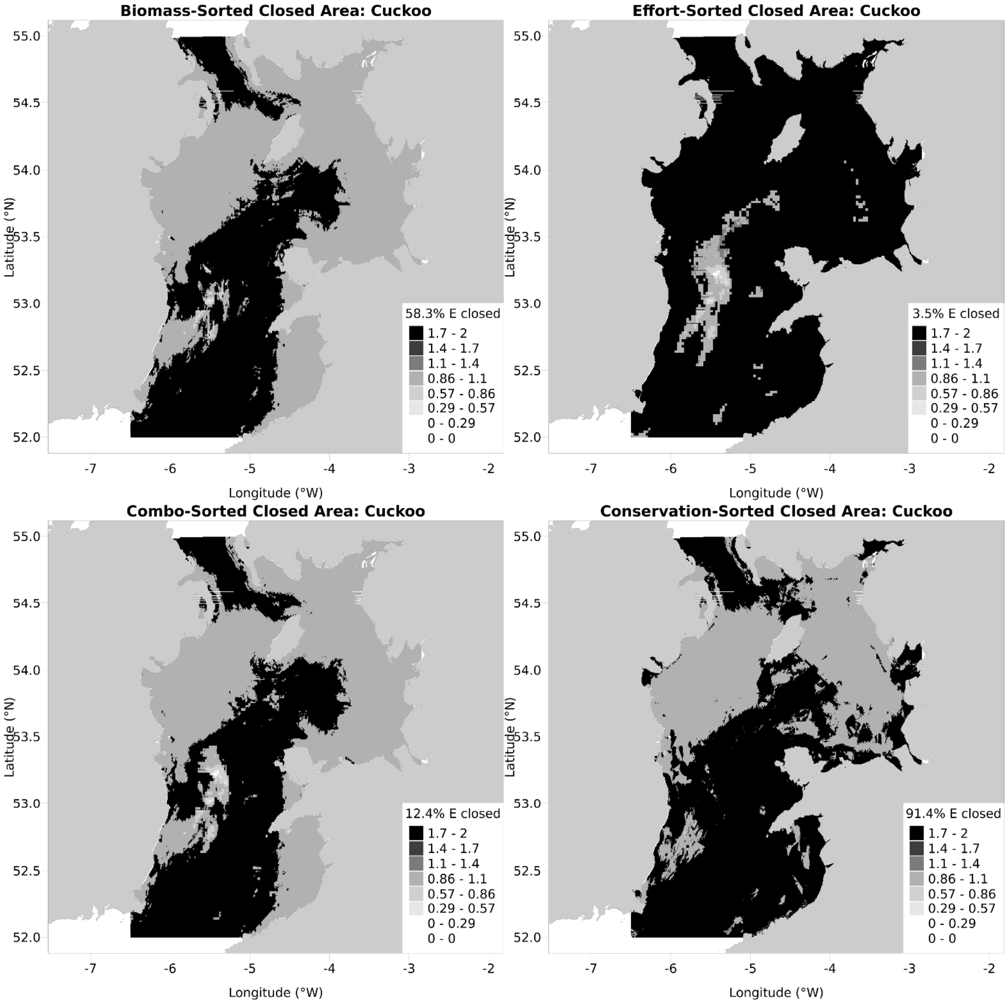


Figure 4: Maps of cuckoo ray closed areas prioritising species biomass, fishing effort, a combination of both, and conservation areas
2230x2230mm (72 x 72 DPI)



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2230x2230mm (72 x 72 DPI)

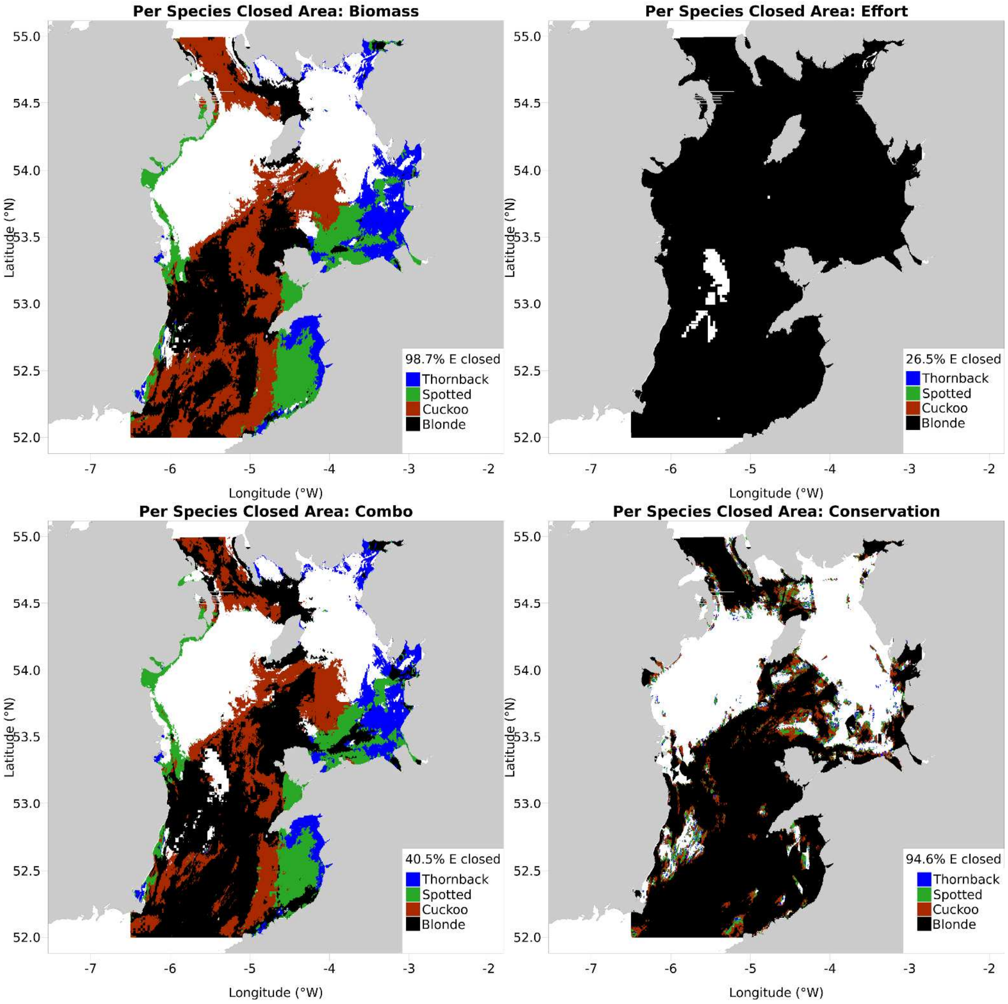
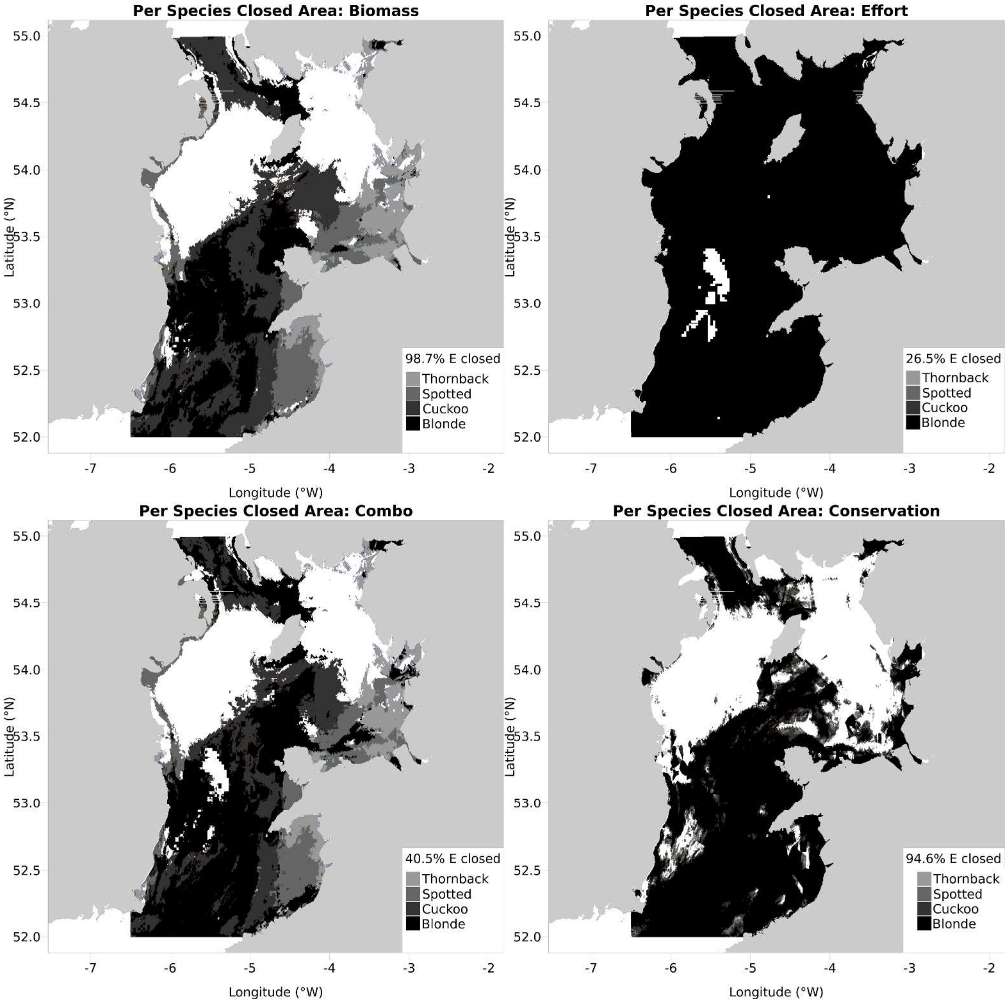


Figure 5: Maps of cumulative closed areas prioritising species biomass, fishing effort, a combination of both, and conservation areas. Areas are successively closed from the most to least vulnerable: cuckoo ray (black), blonde ray (red), spotted ray (green), thornback ray (blue) until each species reaches HRMSY. Legend percentages are the amount of fishing effort displaced

2230x2230mm (72 x 72 DPI)



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2230x2230mm (72 x 72 DPI)