Decision support tools for dynamic management

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Running head: Decision support tools

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Abstract.

Spatial management is a valuable strategy to advance regional goals for nature conservation, economic development, and human health. One challenge of spatial management is navigating

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the prioritization of multiple features. This challenge becomes more pronounced in dynamic management scenarios, in which boundaries are flexible in space and time in response to changing biological, environmental, or socioeconomic conditions. To implement dynamic management, decision support tools are needed to guide spatial prioritization as feature distributions shift under changing conditions. Marxan is a widely applied decision support tool designed for static management scenarios but its utility in dynamic management has not been previously evaluated. EcoCast is a new decision support tool explicitly developed for the dynamic management of multiple features, but is lacking some of Marxan's functionality. In this study, we compared the capacity of these two decision support tools to prioritize four marine species in a dynamic management scenario for fisheries sustainability. We successfully configured Marxan to operate dynamically on a daily time-scale to parallel EcoCast. The relationship between EcoCast solutions and the underlying species distributions was more linear and less noisy, while Marxan solutions had more contrast between waters that were good and poor to fish. Neither decision support tool clearly outperformed the other; the appropriateness of each will depend on management purpose, resource manager preference, and technological capacity of tool developers.

1. Introduction

Spatial management strategies such as Marine Protected Areas and National Parks have been successfully applied to manage natural resources and disturbances (Margules and Pressey 2000). To implement spatial management, decisions must be made about which areas to prioritize for protection (Pressey et al. 2007). These decisions become more arduous when multiple features are managed under the same plan, for example resources such as protected species and productive areas, and disturbances such as extractive operations and temperature anomalies. To help navigate spatial trade-offs, a suite of decision support tools has been developed to allow for systematic decision-making about the value of areas towards meeting management priorities, for example Marxan (Ball et al. 2009), C-Plan (Pressey et al. 2009) and Zonation (Moilanen et al. 2009). Recently, dynamic management - a subset of spatial management in which boundaries are automatically updated in space and time (Lewison et al. 2015) - has gained traction as a solution for managing features with changing distributions, such as highly migratory species (Eveson et al. 2015). To implement dynamic management, decision support tools are needed to continuously balance spatial trade-offs as feature distributions shift under each new set of conditions.

Dynamic management has been applied in atmospheric (Sampson and Schrader 2000), marine (Hazen et al. 2017), and terrestrial (Quayle et al. 2004) ecosystems to manage features that vary too quickly (days to years), and over spatial scales that are too large (100s to 1000s of kms) to be accommodated by traditional static management strategies. Operational dynamic management strategies function by acquiring data on current or forecasted biological, environmental, and/or socioeconomic conditions, then predicting and prioritizing target features in real-time or forecasted conditions, and lastly disseminating final products that communicate management recommendations (Welch et al. 2018). This entire process is automated to repeat at an appropriate temporal frequency, for example daily, weekly, or monthly. While static approaches require a one-time prioritization of features, dynamic approaches must repeatedly navigate prioritization at each time-step. Owing to the complexity of this task, most dynamic management strategies to date have focused on one target feature, for example whales (Hazen et al. 2017), hurricanes (Sampson and Schrader 2000), or wildfires (Quayle et al. 2004).

EcoCast was one of the first examples of an applied multi-feature dynamic management strategy (Hazen et al. 2018, Welch et al. 2018). Designed to improve the sustainability of a swordfish fishery off the U.S. west coast, EcoCast aims to help fishers avoid bycatch of protected species while maintaining swordfish (*Xiphias gladius*) catch. Each day, EcoCast acquires the latest available data on ocean conditions, predicts the distributions of each species, and then prioritizes species using an algebraic algorithm to produce the final product, which is a continuous fishing suitability map that presents waters as better and poorer to fish. While other examples of operational dynamic fisheries management exist, they are often only applicable to single species management (Howell et al. 2008, Hazen et al. 2017), or require bycatch events to occur before management actions are initiated, e.g. move-on rules and grid-based closures (Dunn et al. 2016). Hereafter, EcoCast refers to the algebraic algorithm used to prioritize multiple features, as opposed to the specific dynamic management scenario for the drift gillnet fishery.

The decision support tool Marxan (Ball et al. 2009) was explicitly developed to find solutions to the type of multi-feature trade-off problem EcoCast is trying to solve. Marxan uses a simulated annealing algorithm to identify complementary sets of areas that address management priorities while minimizing costs. Although Marxan was intended as a static management tool, its consideration of complementarity and overall solution costs might confer advantages over EcoCast when applied in dynamic management scenarios, as EcoCast does not explicitly incorporate these principles. Marxan has been frequently applied in fisheries contexts (Klein et al. 2010, Metcalfe et al. 2015), and has also been applied to find static solutions that accommodate dynamic features like frontal systems, upwelling, and highly migratory species (Lombard et al. 2007, Grantham et al. 2011, Roberson et al. 2017). However, using static solutions to manage dynamic features has drawbacks such as increased opportunity costs and larger area requirements (Dunn et al. 2016, Hazen et al. 2018), thus it is valuable to explore Marxan's utility as a decision support tool for dynamic management.

By design, dynamic management strategies update their boundaries regularly to adapt to changing conditions. This built-in flexibility also allows dynamic strategies to be responsive to changing management priorities; while static management approaches require implementation phases to adjust to new priorities, dynamic schemes can adopt changing priorities without requiring new management plans (Hazen et al. 2018). EcoCast was designed to be responsive to changing management priorities, which could reflect recent bycatch events, or new interaction risks as species shift in distribution. This responsiveness is achieved by adjusting species weightings in the algebraic algorithm, which affects the relative importance of each species in the final product, e.g. species X is twice as important as species Y. In Marxan, managers can define targets for feature protection, for example to protect 20% of each species' habitat, and these percentage targets could be updated as management priorities change. However, it is important to test tool performance under changing management priorities to ensure intended outcomes are achieved.

With improving computational capacity and data availability, management scenarios are able to incorporate increasing numbers of features. Static management scenarios routinely include tens (Fernandes et al. 2005, Roberson et al. 2017) to hundreds (Carroll et al. 2010, Welch and McHenry 2018) of features. The incorporation of additional features likely incurs costs, which may be direct monetary costs of implementation or indirect monetary costs of larger area requirements and the displacement of extractive operations. Incurred cost may also be measured in terms of efficiency, in which the inclusion of additional features reduces the ability to manage any individual feature, compromising the overall performance of the scenario and reducing return on investment (Laitila and Moilanen 2012). As dynamic management expands to explore multi-feature prioritization, these costs and their variability in time must be quantified.

Here, we compare the performance of two decision support tools: EcoCast's algebraic algorithm and the simulated annealing algorithm underlying Marxan, to manage multiple marine species in a dynamic management scenario. Our aims are to: 1) configure Marxan to operate dynamically, 2) evaluate the tools' abilities to respond to changing management priorities, and 3) quantify the tools' efficiency costs of managing additional species. Assessing decision support tool performance is a key step in developing dynamic management strategies that can accommodate climate variability and change.

2. Methods

2.1 Dynamic management scenario

The two decision support tools were evaluated using a dynamic management scenario (see Figure 1 in Welch et al. (2018) for a procedural flowchart of dynamic management scenario development) designed to improve the sustainability of a U.S. swordfish fishery that experiences bycatch of protected leatherback turtles (*Dermochelys coriacea*), blue sharks (*Prionace glauca*), and California sea lions (*Zalophus californianus*) (Hazen et al. 2018). The dynamic management scenario aims to identify areas that are better and poorer to fish each day, based on the distributions of swordfish and the bycatch species. To estimate species' distributions, boosted regression tree models with a binomial (presence-absence) response were built and validated for each of the four species, following the same methods as described in Brodie et al. (2018). Environmental covariates were obtained from a California Current System configuration of the Regional Ocean Modeling System with data assimilation (Neveu et al. 2016). Species data included fisheries observer data for swordfish and blue sharks, and satellite-tracking data for leatherback turtles, blue sharks, and sea lions (data described in Hazen et al. 2018).

For the purpose of this analysis, species distributions were hindcast for 213 days in three periods that contained the majority of the species data used to fit the models: October-November 1997 (μ=16.1°C), April 2003 (μ=10.2 °C), and August-November 2005 (μ=17.9 °C). These periods represent a range of sea surface temperatures in the study region, used here as a surrogate for ocean state (Appendix S1, Fig. S1). For each day in the hindcast period, the species distribution models were predicted over the day's environmental covariates to produce real-time habitat suitability maps ranging from one to zero (highest and lowest suitability, respectively). These daily habitat maps were then prioritized as specified by management priorities using the EcoCast and Marxan decision support tools (described below) to produce fishing suitability maps for each day. Management priorities for both tools were set using species weightings, which are decimal values between negative and positive one. Weightings for bycatch species are negative, and weightings for swordfish are positive.

2.2. EcoCast decision support tool

EcoCast uses an algebraic algorithm to prioritize the species habitat suitability maps. The habitat suitability map for each species is multiplied by its weighting, which determines each species' relative contribution to the final product. The absolute values of the weightings sum to one, such that in a management scenario with equal priority for four species, the three bycatch species would each be weighted -0.25, and swordfish would be weighted 0.25. The weighted habitat suitability maps are summed to produce a final product showing waters that are better and poorer to fish:

$$E = sp_1*w_1 + sp_2*w_2 + \ldots + sp_N*w_N$$

Where E is the EcoCast output value, sp is the habitat suitability map for each of N species to be considered for management, and w is the respective weighting for each species.

2.3. Marxan decision support tool

We developed a dynamic configuration of Marxan that is responsive to changing management priorities, and produces final products with values that vary continuously from low (poorer to fish) to high (better to fish) to align closely with the functionality of EcoCast. Marxan was run using the R package 'Marxan' (https://github.com/jeffreyhanson/marxan), which was designed to bring the entire Marxan workflow into R.

The daily species habitat suitability maps were input as target features. For bycatch species, which need to be protected from fishing, the raw habitat suitability maps were used. For swordfish, which need to be available for fishing, the habitat suitability maps were subtracted from one such that the highest swordfish suitability had a value of zero and the lowest swordfish suitability had a value of one. Swordfish were input as a target feature as opposed to a cost in order to allow for a consistent method of adjusting management priorities across all species by changing the percentage targets for species protection. To create planning units, the regular raster grid (0.1° x 0.1°) of the habitat suitability maps was converted into polygons. Planning unit cost was the area of each polygon, which was consistent across the domain.

Marxan takes as input the percentage of each target feature to protect, i.e. the percentage of each species' habitat to protect from fishing. The decimal species weightings were converted into protection percentages, e.g. a weighting of -0.25 for bycatch species translated into 25% protection. The swordfish weightings were subtracted from one, and applied to the inverted habitat suitability surfaces, e.g. a weighting of 0.25 translated into protecting 75% of the least suitable swordfish habitat from fishing. A boundary length modifier of zero was used to ensure Marxan was prioritizing achieving weighting targets over solution compactness.

Marxan produces binary solutions in which planning units are either protected or unprotected. To generate final products with continuously-varying fishing suitability, Marxan was run 1000 times for each day to produce maps of selection frequency in which planning units were valued between zero and 1000 (unimportant and critically important for meeting weighting targets, respectively). Selection frequency was multiplied by negative one so that waters that are better to fish are valued higher (near zero), and waters that are poorer to fish are valued lower (near -1000), consistent with the directionality of EcoCast.

2.4. Decision support tool comparison

The ability of the EcoCast and Marxan tools to respond to changing species management priorities was compared across three runs in which leatherback turtles/swordfish were weighted -.3/.7, -.5/.5, and -.7/.3 in both tools. Efficiency costs of managing additional species were evaluated between single-species runs (leatherback turtles-only), two-species runs (leatherback turtles and swordfish), three-species runs (leatherback turtles, swordfish, and blue shark), and four-species runs (leatherback turtles, swordfish, blue shark, and sea lion). For the multi-species configurations of EcoCast, the input species for each run were weighted equally, and for Marxan, input species were weighted at +/-.5. For each run and each hindcast day (n=213), the EcoCast and Marxan algorithms were applied to prioritize the species habitat suitability maps to produce daily final products that indicated fishing suitability. Then, habitat suitability values for each input species and output values of fishing suitability from both tools were extracted at 3000 points distributed evenly in space and time across the hindcast period. To allow for comparison between EcoCast and Marxan, the output values for both were rescaled between zero and one to match the scale of species habitat suitability.

Tool performance was evaluated based on the extracted relationships between habitat suitability for each species (species inputs) and fishing suitability in the final EcoCast and Marxan products (tool outputs). Relationships were evaluated within the scope of three management implications: predictability, interpretability, and the strength of management recommendation (Table 1, Fig. 1). Predictability, or the strength of relationships between species inputs and tool outputs, was evaluated using r-squared values of generalized additive models (GAMs; R package 'mgcv') fit between each tool output and each species input. High predictability (high r-squared values) gives managers confidence that species habitat suitability is strongly reflected in tool outputs. Interpretability, or the consistency of the relationship between species inputs and tool outputs, was evaluated using the effective degrees of freedom from the fitted GAM (Appendix S2). High interpretability (low degrees of freedom) means that tool outputs respond in a consistent way to changes in species inputs, facilitating achievement of expected management outcomes. The strength of management recommendations, or the range of fishing suitability in the final product, was evaluated using the slopes and y-intercepts of linear regressions fit between each tool output and each species input. Stronger management recommendations (steeper slopes, extreme y-intercept values) mean there is more contrast between waters that are good and poor to fish, while lower ranges produce more ambiguity. Metrics from both non-linear and linear fits were used in tandem because optimal relationships could be either non-linear or linear.

All analyses were completed in R version 3.4.1. The R functions for running both EcoCast and Marxan and sample data are available at https://github.com/HeatherWelch/Decision-support-tools-for-dynamic-management.

3. Results

3.1. Qualitative comparison

The dynamic configuration of Marxan produced fishing suitability maps that were spatially similar to those produced by EcoCast (Fig. 2). Both tools identified comparable waters to protect leatherback turtles from fishing and to maintain for fishing swordfish (Fig. 2B,C; maps 1,2). However areas of overlapping distributions for swordfish and bycatch species (e.g. north of 40˚N) were valued as neutral fishing suitability by EcoCast, because the opposing weightings canceled out the contributions of each species. This did not occur in Marxan, which explicitly prioritizes areas that are suitable for bycatch species and also unsuitable for swordfish (Fig. 2B,C, map 3). An animation of EcoCast and Marxan outputs across the 213 hindcast days is available at https://heatherwelch.shinyapps.io/welch_et_al_algorithms/.

3.2. Responsiveness to changing management priorities

Both tools were responsive to changing management priorities, which were reflected in the species weightings (Fig. 3). Slopes were always negative for bycatch species and positive for swordfish, meaning that waters deemed better to fish had lowest and highest leatherback turtle and swordfish suitability, respectively. Both tools were affected by changing ocean state, indicated by sea surface temperature. Relationships between species inputs and tool outputs were markedly different between warm and cold periods, though the difference was more pronounced in Marxan than in EcoCast (Fig. 3). The effect of ocean state was especially apparent in the relationship between Marxan and leatherback turtle habitat suitability, where it was most pronounced at extreme leatherback turtle weightings (-.7). For EcoCast, changing species weightings primarily affected r-squared values; more extreme weightings for a given species increased the r-squared value for that species (Table 2). For Marxan, changing weightings primarily affected the y-intercept; the more extreme the weightings, the more extreme the y-intercept, i.e. the y-intercept moved closer to y-max (one) for leatherback turtles and y-min (zero) for swordfish.

3.3. Efficiency costs of managing additional species

When moving from one to four managed species, r-squared values averaged across input species for EcoCast and Marxan were reduced from 1.00 to 0.39 and 0.90 to 0.27, respectively (Table 3). In EcoCast, species are indirectly affected by the inclusion of species with which they are correlated. For example, leatherback turtles and swordfish had similar r-squared values (0.49 and 0.53, respectively) in the two-species run. However when blue sharks were added, which are positively correlated with leatherback turtles (r = 0.63, Appendix S3, Fig. S1), the swordfish r-squared decreased to 0.20, and the leatherback turtle r-squared increased to 0.63. In this EcoCast example, protecting blue sharks effectively increases the protection of leatherback turtles as well. When sea lions were added in the four-species run, the inverse management priorities and inverse correlations between swordfish and sea lions (r=-0.76, Appendix S3, Fig. S1) translated into the two species having more combined contribution to the final product, ultimately decreasing the protection of leatherback turtles (an r-squared change from 0.63 to 0.36).

For Marxan, interspecies correlations are handled implicitly as the same habitat can satisfy management priorities for multiple species. Therefore, r-squared values for input species were unchanged between the two-, three-, and four- species runs (Table 3). Weighting targets for blue sharks and sea lions were already met in the two-species run (leatherback turtle and swordfish) due to the direct leatherback turtle/blue shark correlation and the inverse swordfish/sea lion correlation. Both tools displayed trends of decreasing spreads between the mean bycatch species y-intercept and the swordfish intercept and flattening mean slopes as additional species were added. This trend persisted for EcoCast when the two-, three-, and four-species runs were rescaled from zero to one to remove the effect of decreasing weighting magnitude (Appendix S4, Fig. S1, Table S1). Mean slope was always steeper and mean spread was always greater for Marxan across all weighting runs (Table 3, Fig. 4).

4. Discussion

Decision support tools provide a method of systematically navigating spatial prioritization, increasing the transparency and defensibility of management scenarios (Margules and Pressey 2000). While decision support tools are well established in the field of static management, comparable tools for dynamic management have not been explored, due in part to the infancy of the field. In this study, we used a dynamic management scenario for fisheries sustainability to compare the performance of two decision support tools: EcoCast's algebraic algorithm, and Marxan's simulated annealing algorithm. While EcoCast was explicitly designed as a fisheries sustainability tool and Marxan is intended to be used as a conservation planning tool, Marxan has additional functionality which could confer advantages over EcoCast. Relationships between species habitat suitability (species input) and fishing suitability (tool output) were generally more predictable and interpretable in EcoCast, whereas Marxan produced stronger management recommendations. However, neither decision support tool clearly outperformed the other. Therefore, the appropriateness of each tool will depend on management purpose, resource manager preference, and the technological capacity of tool developers (Table 4).

For dynamic management scenarios that prioritize responsiveness to changing management priorities, EcoCast's algebraic algorithm may be a more appropriate tool. Changing management priorities were tested by varying the species weightings; the range of useable species weightings is reduced in Marxan due to the effects of ocean state and species weightings on Marxan's selection frequency. Selection frequency is affected by the total amount of habitat available, and the patchiness of available habitat (Carwardine et al. 2007), both of which can vary significantly with ocean state. The effect of ocean state was most pronounced in Marxan (Fig. 3, Table 2), especially under extreme species weightings, and for leatherback turtles which have markedly different distributions between warm and cold ocean states (Benson et al. 2011). Additionally, the relationship between selection frequency and species inputs can break down when species weightings are extreme (+/-.9) or near zero. Under extreme weighting scenarios, Marxan must protect nearly all of a given species' habitat, leading to a wide range of habitat suitability values with high selection frequencies. Conversely, when species weightings are set close to zero, there are many different possible solutions to meet weighting targets, causing low selection frequencies. The response of Marxan's selection frequency to ocean state and species weightings effectively caps the range of weightings beyond which decreased predictability and interpretability limit utility of the final product.

For dynamic management scenarios that aim to manage many features, Marxan may be a more appropriate tool, due to its increased ability to preserve contrast between waters that are better and poorer to fish, and it's implicit handling of interspecies correlations. The relationships between species inputs and tool outputs became compressed in EcoCast as more species were added, leading to a reduced range of fishing suitability and weaker management recommendations in the final product (Fig. 4, Table 3). In contrast Marxan, which operates on the principal of complementarity, was able to preserve a larger range of fishing suitability as species were added, ultimately producing stronger management recommendations. Additionally, EcoCast is more sensitive to interspecies correlations than Marxan, which can produce unintended management outcomes as additional species are managed. Not surprisingly, the performance of both tools for any one species was compromised as more species were added. Recently, efforts to manage biodiversity have moved away from single-species approaches towards holistic approaches that consider the interdependence of ecosystem components. While this shift has many positive aspects, cautionary tales from disciplines as diverse as fisheries (Vinther et al. 2004), ESA listed species recovery (Harvey 2002), and conservation planning (Laitila and Moilanen 2012) indicate there may be a point of diminishing returns, beyond which the inclusion of additional features compromises management outcomes.

Resource manager preference will also affect decision support tool selection. In Marxan, management priorities are interpreted absolutely, such that managers can explicitly state how much of each species habitat is protected or maintained for extractive uses. In the EcoCast algorithm, the management priorities reflected in species weightings are interpreted relatively, such that managers must decide how much each species is prioritized in relation to other species. Additionally, the EcoCast algorithm's relative interpretation of management priorities requires adjustments as new species are added because the absolute values of the species weightings sum to one. In contrast, management priorities can remain unchanged in Marxan as species are incrementally added, facilitating the uptake of new species data as it becomes available. Explicit criteria for setting meaningful management priorities are well-explored in the Marxan literature (e.g. Pressey et al. 2015). Some criteria are only relevant to Marxan's absolute interpretation of management priorities, however, other criteria could be leveraged to inform EcoCast's relative interpretation of management priorities, such as scaling priorities relative to feature rarity, decline, or threat (Lieberknecht et al. 2010). The utility of setting relative versus absolute management priorities will depend on manager preference and their comfort interpreting the parameterization and outputs of different tools.

Additionally, resource managers might favor Marxan for its well-established track record in applied management. Marxan is the most widely applied decision support tool for spatial prioritization and has been used to develop a variety of operational management scenarios such as integrated land-sea planning, terrestrial and marine protected areas, and conservation corridors (Fernandes et al. 2005, Smith et al. 2008, Adams et al. 2017). In contrast, the EcoCast algorithm is relatively new and has only one example of applied use (Hazen et al. 2018). Established practices frequently have significant inertia, and resource managers may prefer the Marxan algorithm for its greater familiarity.

Lastly, the technological capacity of tool developers will affect decision support tool selection. The EcoCast algorithm is computationally simple, but this simplicity comes at a cost of reduced flexibility. Conversely, the Marxan algorithm is more complex to run, yet it has much greater flexibility. In Marxan, tool developers can adjust parameters that control the cost of planning units, the penalties for missing weighting targets, and the compactness of solutions, which were not explored here. Additionally, run time might affect tool selection, which is greatly minimized in EcoCast (in our tests, 3.2 seconds per day to find a solution for a four-species run versus 156 seconds in Marxan).

4.1. Wider applications

Other decision support tools that were developed for static applications, such as Zonation (Moilanen et al. 2009) and C-Plan (Pressey et al. 2009), could be explored in dynamic capacities and might provide functionalities beyond those offered by Marxan or EcoCast. Static conservation planning exercises that include dynamic features must first simplify feature variability, for example by identifying persistent critical habitat areas such as breeding grounds (Game et al. 2009), or finding features' average distributions across time (Grantham et al. 2011, Lombard et al. 2007). However, these simplified representations can result in significant losses of information on feature variability. Applying the EcoCast algorithm or the dynamic configuration of Marxan in these scenarios can preserve variability by allowing scales of management to align with scales of feature variability, as opposed to forcing scales of feature variability to align with scales of management.

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Tables.

Table 1. Management implications based on the relationship between species inputs and tool outputs.

Management implication	Performance metric*	Definition	Interpretation	Optimal values
Predictability	R-squared (GAM)	The proportion of variance explained by the model	Strength of relationship between tool outputs and species inputs	High
Interpretability	Effective degrees of freedom (GAM)	The number of values in the final model that are free to vary	Consistency of relationship between tool outputs and species inputs	Low
Strength of management recommendation	Slope (LM)	The change in y for a given change in x	The change in tool output for a given change in species input	Bycatch species: negative and steep; swordfish: positive and steep
Strength of management recommendation	Y-intercept (LM)	The y value when x=0	The tool output for a species input of 0	Bycatch species and swordfish are close to maximum and minimum tool output values, respectively

* Performance metrics were derived from both non-linear (generalized additive models: GAMs), and linear (LM) fits.

Table 2. Effect of changing management priorities * on performance metrics defined in Table 1 for the EcoCast and Marxan tools.

	EcoCast		Marxan	
Weighting run	Leatherback	Swordfish	Leatherback	Swordfish
	R-squared			
-0.3/0.7	0.35	0.89	0.52	0.36
-0.5/0.5	0.49	0.53	0.50	0.36
-0.7/0.3	0.82	0.11	0.46	0.33
	Effective degrees of freedom			
-0.3/0.7	3.9	1	2.7	1
-0.5/0.5	2.4	1	3.2	1
-0.7/0.3	1	2.8	4.1	1
	Y-intercept			
-0.3/0.7	0.78	0.62	0.86	0.56
-0.5/0.5	0.74	0.61	0.73	0.28
-0.7/0.3	0.70	0.59	0.52	0.08
	Slope			
-0.3/0.7	-0.02	0.23	-0.29	0.30
-0.5/0.5	-0.12	0.14	-0.42	0.46
-0.7/0.3	-0.22	0.05	-0.40	0.46

* Management priorities are reflected in the species weighting runs, which are negative for leatherback turtles and positive for swordfish.

Table 3. EcoCast and Marxan performance metrics for one-, two-, three-, and four-species weighting runs.

	EcoCast					Marxan				
Weighting run	Leatherback	Swordfish	Blueshark	Sealion		Leatherback	Swordfish	Blueshark	Sealion	
R-squared[a]					Mean					Mean
Four-species	0.36	0.64	0.07	0.48	0.39	0.50	0.36	0.05	0.16	0.27
Three-species	0.63	0.20	0.29		0.37	0.50	0.36	0.05		0.30
Two-species	0.49	0.53			0.51	0.50	0.36			0.43
One-species	1.00				1.00	0.90				0.90
Effective Degrees of freedom[a]					Mean					Mean
Four-species	3	1	3.5	1.7	2.3	3.2	1	4	1.9	2.5
Three-species	1	1	1		1	3.2	1	3.9		2.7
Two-species	2.4	1			1.7	3.2	1			2.1
One-species	1				1	1.2				1.2
Y-intercept[b]					Spread					Spread
Four-species	0.64	0.54	0.63	0.63	0.09	0.73	0.28	0.64	0.61	0.38
Three-species	0.68	0.59	0.69		0.09	0.73	0.28	0.65		0.41
Two-species	0.74	0.61			0.13	0.73	0.28			0.45
One-species	0.65					1.11				
Slope[a]					Mean					Mean
Four-species	-0.04	0.12	-0.03	-0.10	0.07	-0.41	0.45	-0.16	-0.25	0.32
Three-species	-0.14	0.06	-0.13		0.11	-0.41	0.45	-0.16		0.34
Two-species	-0.12	0.14			0.13	-0.42	0.46			0.44
One-species	-0.37				0.37	-1.18				1.18

[a] For r-squared values, degrees of freedom, and slopes, row means are calculated using the absolute values of each cell.

[b] For y-intercepts, spread is the difference between the mean bycatch species intercept and the swordfish intercept.

Table 4. Decision support tool summary with regards to management purpose, manager preference, and technological capacity of tool developers.

		EcoCast	Marxan
Management purpose			
	Predictability	Higher	Lower
	Interpretability	Higher	Lower
	Strength of management recommendation	Weaker	Stronger
	Sensitivity to ocean state	Lower	Higher
	Sensitivity to Interspecies correlations	Higher	Lower
Manager preference			
	Weighting interpretation	Relative	Absolute
	Examples of applied use	Many	Few
Technological capacity of tool developers			
	Run time (seconds)	3.2	156
	Complexity	Lower	Higher
	Flexibility	Lower	Higher

Figure captions.

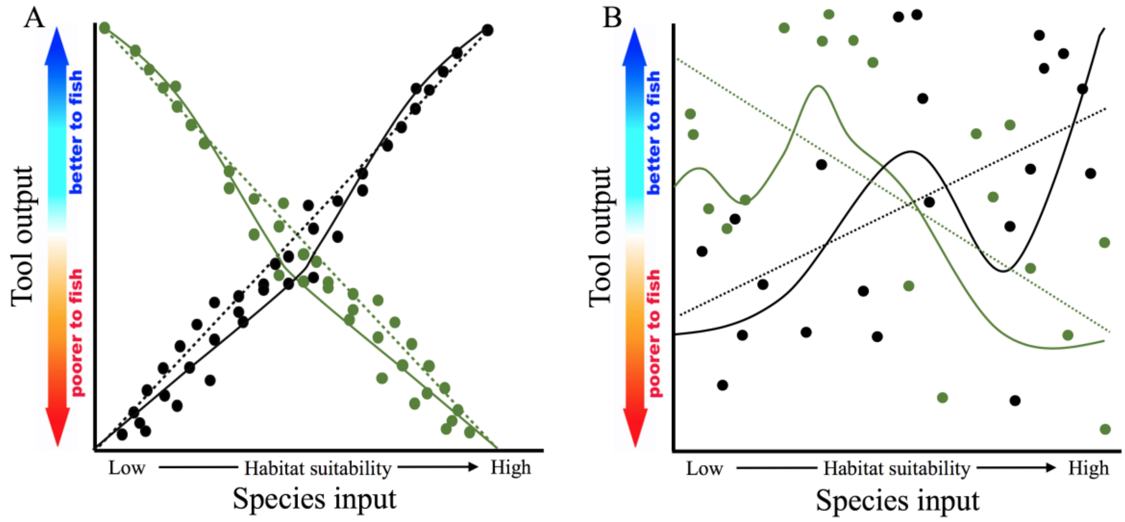

Figure 1. Two scenarios of potential relationships between species habitat suitability (species inputs) and fishing suitability in final EcoCast/Marxan products (tool outputs). Plots show simulated data for an example bycatch species (green) and a target species (black). Solid lines represent non-linear fits (generalized additive model: GAM), dotted lines represent linear fits (linear model: LM). A. An optimal scenario characterized by high predictability (high r-squared; GAM), high interpretability (low degrees of freedom; GAM), and strong management recommendations (steep slopes and y-intercepts close to maximum and minimum tool output values; LM). B. A problematic scenario characterized by low predictability (low r-squared; GAM), low interpretability (high degrees of freedom; GAM), and weaker management recommendations (flatter slopes and moderate y-intercepts far from potential maximum and minimum tool output values; LM).

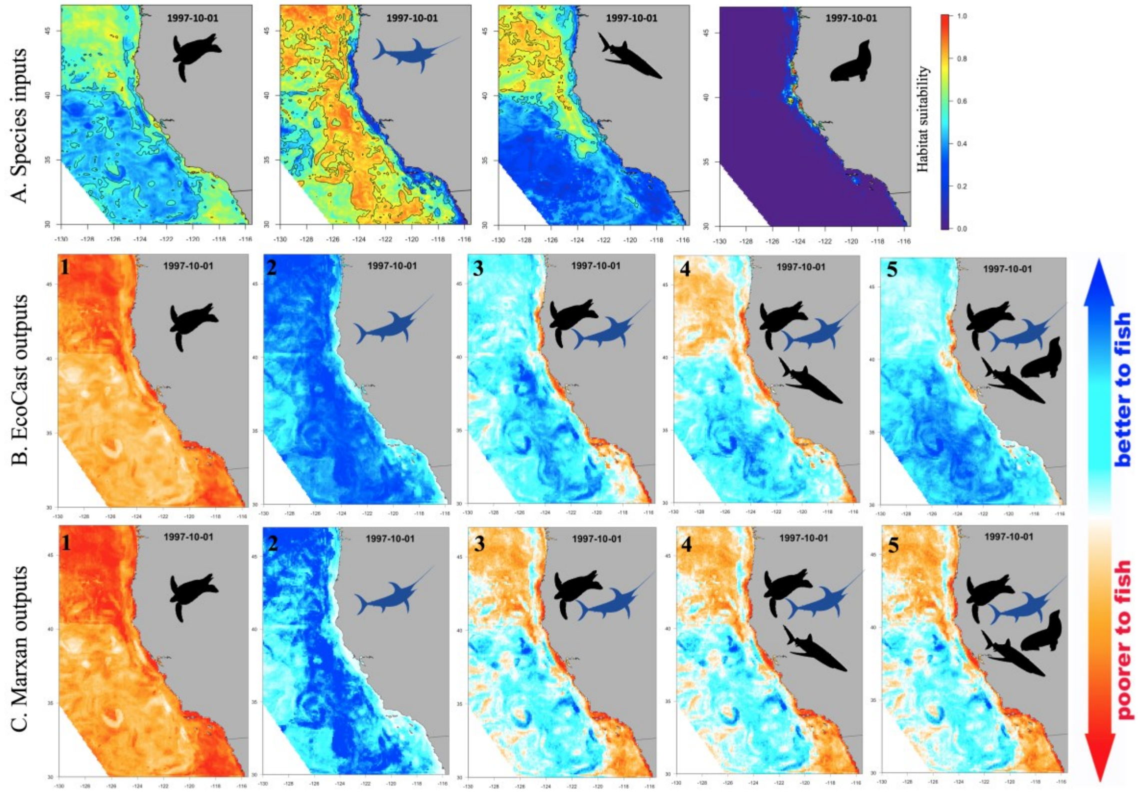

Figure 2. Predicted species distributions and EcoCast and Marxan solutions for an example day, 1997-10-01. Row A. Habitat suitability layers for each species: leatherback turtle, swordfish, blue shark, and California sea lion. Row B. EcoCast outputs with equal weightings for each species; scalebar reflects the output of the algebraic algorithm, and range depends on both the number of input species and the magnitude of the species weightings. Row C. Marxan outputs with +/-0.5 weighting for each species; scalebar reflects inverted selection frequency with a possible range of 0 to -1000. From left to right, rows B & C demonstrate weighting runs for one to four species. For each map, species icons show which species were input into the tools.

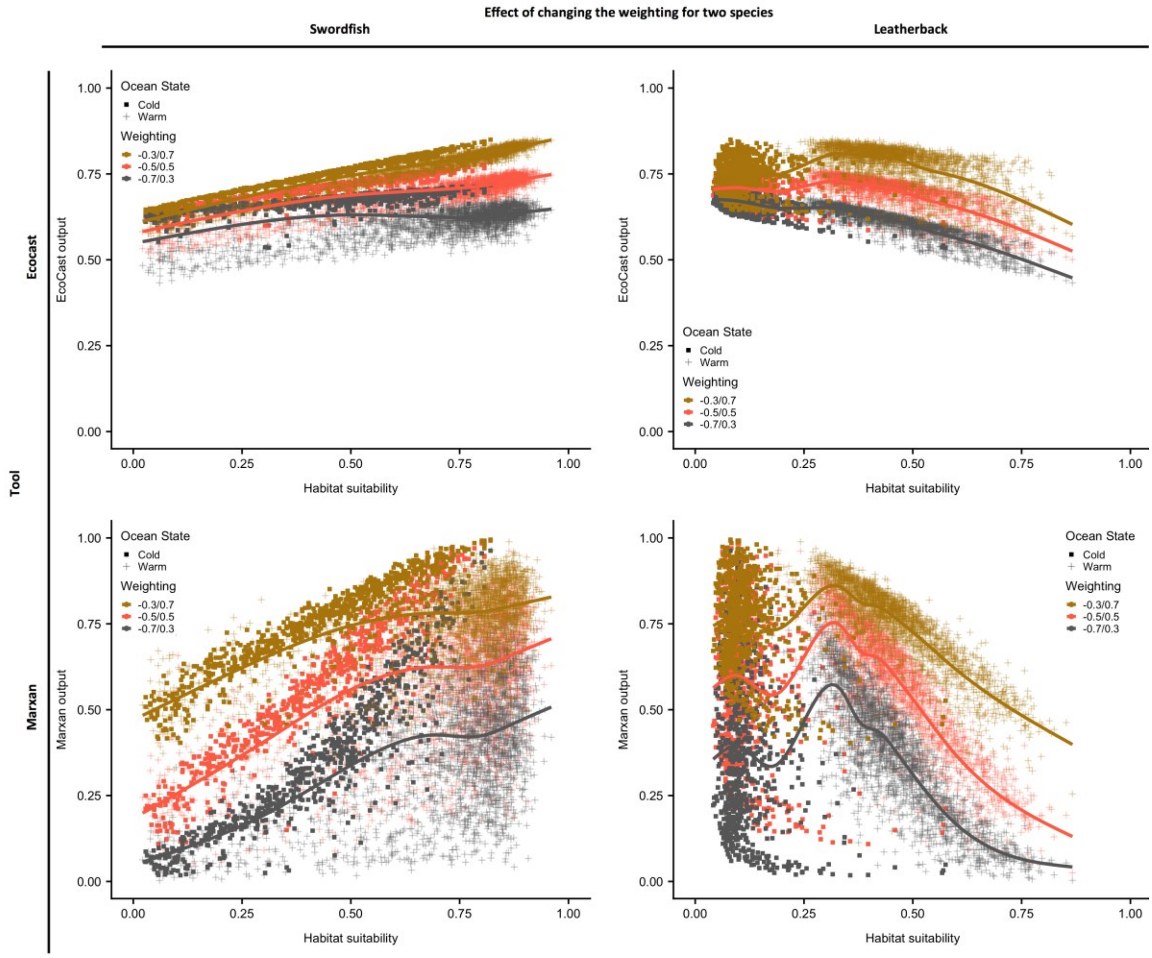

Figure 3. Effect of changing management priorities for leatherback turtles and swordfish on EcoCast (top row) and Marxan (bottom row) tool outputs relative to species habitat suitability. Curves show generalized additive models fit to each weighting run.

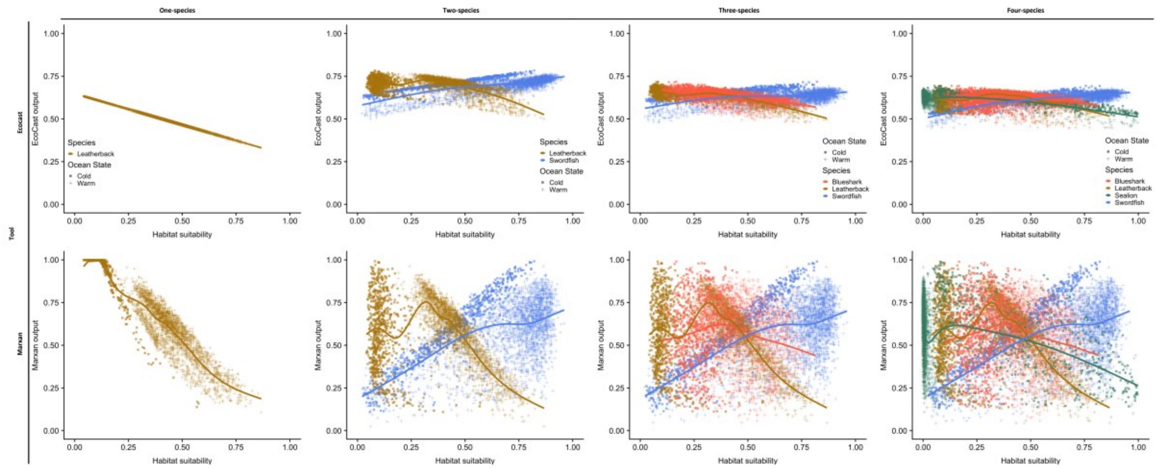

Figure 4. Effect of managing additional species on EcoCast (top row) and Marxan (bottom row) tool outputs relative to species inputs in single-species (column 1), two-species (column 2), three-species (column 3), and four-species (column 4) weighting runs. Curves show generalized additive models fit to each weighting run.