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Process for Analyzing Trade-offs between Fishing and Vulnerable Marine Ecosystem Protection

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Abstract

Regional Fishery Management Organizations (RFMOs), including the North Pacific Fishery Commission (NPFC), have been called on to take action to prevent Significant Adverse Impacts (SAIs) to Vulnerable Marine Ecosystems (VMEs). Currently, the NPFC is still developing approaches to using different kinds of data to quantitatively define VMEs and assess SAIs. A preliminary trade-off analysis was conducted in the Northeast Pacific drawing on Canadian Sablefish fishery data to describe the key steps in identifying VME areas for protection from SAIs given currently available data. The proposed process includes nine general steps modelled after the South Pacific RFMO (SPRFMO) VME trade-off analysis and follows the basic principles of systematic conservation planning: (1) identifying and involving stakeholders, (2) identifying goals and objectives, (3) defining conservation features and gathering data, (4) setting conservation targets and design principles, (5) identifying cost metrics and gathering data, (6) dividing the planning region into planning units, (7) selecting a decision support tool, (8) completing analysis, and (9) completing sensitivity analysis. Data requirements for the process include identifying VMEs based on species distribution models (SDMs) of VME indicator taxa recognized by the NPFC, as well as fishery and other socioeconomic data. Catch, visual, and other types of data may also be used to identify VMEs. When these are identified, the process outlined below can be followed by NPFC Members to work towards the objective of preventing SAIs to VMEs. The code for this preliminary example of a trade-off analysis is included as Appendix A and data is available at: https://collaboration.npfc.int/node/86

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Context

Bottom fisheries in the high seas account for less than 1% of global fisheries catches (FAO 2020). They are, however, associated with damage to a variety of benthic organisms associated with commercial species. Gear types used in the deep sea include bottom otter trawls, bottom long-lines, deep midwater trawls, sink/anchor gillnets, pots, traps, and tangle nets (Clark and Koslow 2007). Static fishing gear such as longlines may have a lower impact (Pham et al. 2014), however, they still have potential to incur negative impacts on structure forming invertebrates (Sampaio et al. 2012). Fishing can damage biodiversity and alter ecosystem structures and functioning (Devillers et al. 2015). Hence, the Convention of Biological Diversity (CBD) encourages States to minimize adverse impacts on biological diversity (FAO 2020). The United Nations General Assembly (UNGA) resolution 61/105 calls on states and Regional Fisheries Management Organizations (RFMOs) to take action to prevent Significant Adverse Impacts (SAIs) on Vulnerable Marine Ecosystems (VMEs) (UNGA 2006). There are growing conflicts between social-economic drivers of impacts to benthic ecosystems and the need to protect biodiversity, and implementation of marine reserves requires compromise among divergent priorities (Muntoni et al. 2019). Discussions among NPFC Members indicate that spatial management is the most practical approach to protecting VMEs, given the difficulty enforcing compliance following encounters with VME indicator taxa (FAO 2019), although other measures, including gear restrictions, could help protect VMEs. As a result of the 2018 Food and Agriculture Organization of the United Nations (FAO) workshop on VMEs in the NPFC region, it was recommended to conduct formal spatial management planning (FAO 2019). As part of the process, species distribution models (SDMs) should be developed for use in decision support tools, following a model similar to the South Pacific RFMO (SPRFMO) process. The approach focuses on identifying VME protected areas that minimize opportunity and managements costs and conflicts with stakeholders. When implemented, protected areas can contribute to achieving the social and ecological goals for sustainable use of marine natural resources (Devillers et al. 2015).

Introduction

VME indicator taxa are abundant throughout the NPFC Convention Area (CA) (Curtis et al. 2015; Baco et al. 2017; Chu et al., 2019; Curtis and Kiyota, 2020; Du Preez et al. 2020). Evidence has shown that SAIs are already occurring in the NPFC CA (Baco et al. 2020). An FAO/NPFC workshop on the protection of VMEs in the NPFC CA determined that SAIs on corals have and are still likely to occur (FAO 2019). Without changes to the current bottom fishery regulatory conservation and management measures (CMMs), VMEs in the NPFC CA may continue to incur SAIs.

Systematic conservation planning focuses on providing support for decision making around resource use and conservation. It is one of the most highly recommended approaches to conservation planning because it enables a process that is transparent, inclusive, and defensible (Ardron et al. 2010; McIntosh et al. 2017). While systematic conservation planning can be conducted using a variety of methods, the use of decision support tools offers a systematic approach resulting in more objective decision making (Ardron et al. 2014).

Decision support tools have been widely applied in spatial management and trade-off analysis around the world. They are spatially-explicit tools that help resource planners and managers integrate data from ecological, economic, and social systems, assess management alternatives and trade-offs in a transparent way, gain stakeholder involvement, and evaluate progress on achieving management objectives (Center for Ocean Solutions 2011). Decision support tools facilitate the decision-making process by providing different possible scenarios.

The application of decision support tools has largely been to establish Marine Protected Areas (MPAs). In one example of the use of Marxan, Lagasse et al. (2015) found that small reductions (e.g. 1-2%) in trawl fishery landings values could result in protecting as much as 75-95% of predicted coral and sponge habitat in part of Canada's national waters. While most examples of systematic conservation planning are applied to MPA planning, it is also used and recommended for identifying and protecting VMEs (Rowden et al. 2015; Rowden and Cryer 2018).

In 2014, the SPRFMO applied a systematic conservation plan by using predicted distributions of VME indicator taxa with the decision support tool Zonation. The range of identified VME conservation scenarios protected 70-90% of suitable habitat for VME indicator taxa while reducing the fishing footprint by only 0-9.55% (Rowden et al. 2015). In 2017, spatial management areas identified using Zonation software increased the protection of VME habitat from 65% to 84%, while providing slightly better access to fishing grounds (Rowden and Cryer 2018). At a recent FAO/NPFC workshop on VMEs, participants suggested that NPFC and SPRFMO had similar issues and habitats, thus NPFC Members expressed interest in discussing the use of decision support tools like Zonation (FAO 2019).

The result of decision support tools requires careful evaluation, especially in the context of the data used. Tools, such as Marxan, will generate outputs regardless of the quality of data given to them

(Ardron et al. 2014). Ensuring the input data is high quality and representative of the goals of the analysis helps produce a result that is not only effective in achieving the goals, but also accepted with a high level of confidence by scientists, managers, and stakeholders. Use of a decision support tool provides an open and transparent way of viewing information and identifying trade-offs by showing the consequences of each alternative to stakeholders (FAO 2019).

This working paper outlines a systematic conservation planning strategy for identifying VMEs for protection from SAIs in the NPFC CA. It draws on the four key components of conservation planning: (1) evaluating conservation needs, (2) defining objectives, (3) integrating ecosystem and fishery information, and (4) selecting areas to conserve. It includes the use of decision support tools to complete a trade-off analysis to protect VMEs while minimizing impacts to fishery or other stakeholder groups. Given that developing quantitative definitions of VMEs and SAIs is still a work in progress for the NPFC, alternatives are suggested based on currently available information. The process is exemplified by a preliminary study conducted in the Northeastern region of the NPFC CA. In this paper, we draw on data from Canada's Sablefish fishery as a preliminary example of the key steps in a trade-off analysis. Although we have begun preliminary discussions with managers and stakeholders, Canada has not begun a formal trade-off analysis in the Northeast Pacific Ocean. Our goal in this paper is to describe the key steps in undertaking such analyses while drawing on some of Canada's data.

Preliminary study: Northeast Pacific trade-off analysis

A preliminary study was completed to test a process for conducting trade-off analysis for minimizing impacts to fisheries while protecting VMEs in the NPFC CA. This study focuses on the Northeastern region of the NPFC CA (Figure 1). The region contains several areas identified as ecologically and biologically significant areas (EBSAs) in 2013 by the Convention on Biological Diversity (CBD 2014). Long term research in the area has shown or predicted the presence of NPFC VME indicator taxa (Curtis et al. 2015; Chu et al. 2019; Du Preez et al. 2020) which overlaps with an active Sablefish fishery. The goal of the preliminary study was to outline key steps to follow when using decision support tools to identify potential areas for VME protection while minimizing the economic loss to the Sablefish fishery. The code and how to access data for this trade-off analysis preliminary example is included in Appendix A.

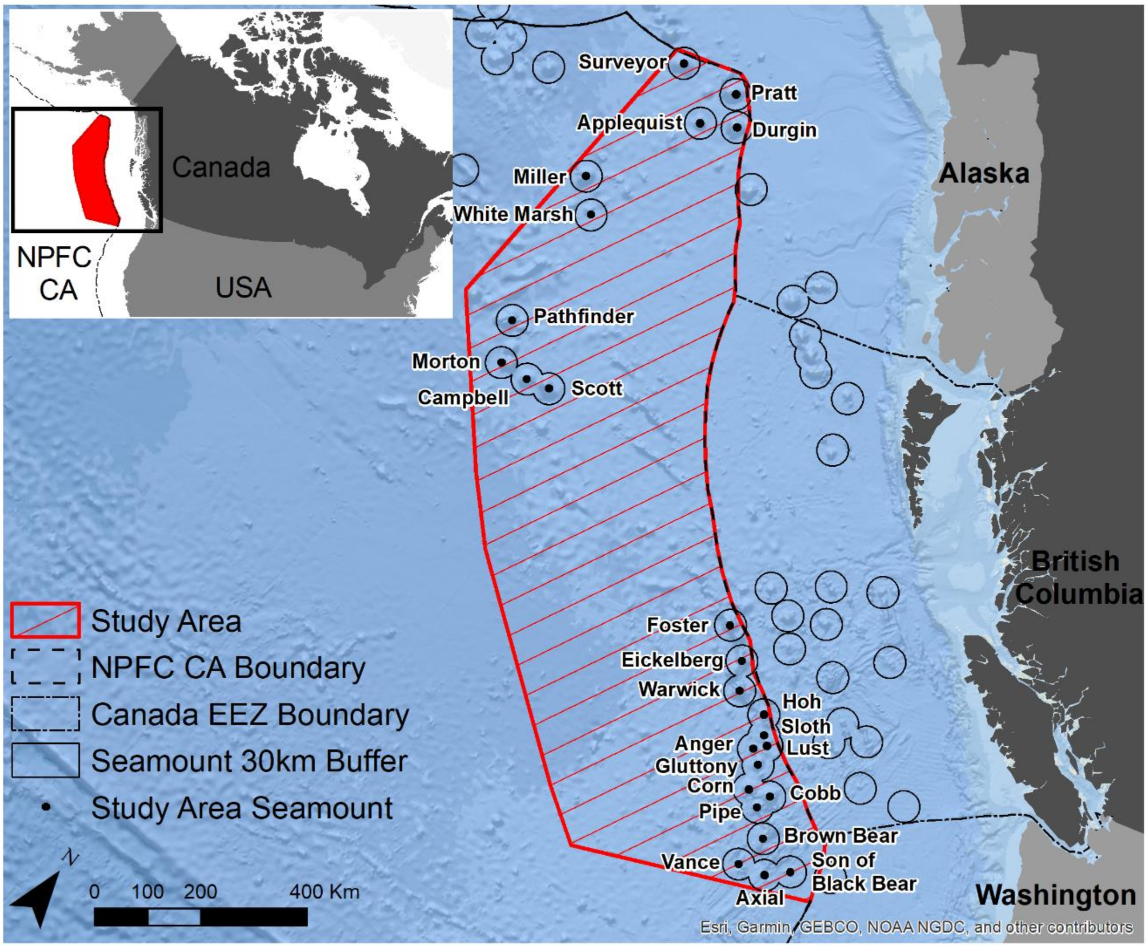

Figure 1. Study area for the preliminary trade-off analysis to minimize fishing impacts while protecting VMEs in the Northeastern NPFC CA.

FAO (2020) defines a fishery "in terms of some or all of the following: people involved, species or type of fish, area of water or seabed, method of fishing, class of boats and purpose of the activities." A small Canadian commercial fleet operates the Sablefish fishery in this area. It is mostly confined to national waters; however, a small seamount fishery extends into the Northeast portion of the NPFC CA. The fishery uses longline hook and trap gear. Trawl gear is not permitted in the seamount fishery (DFO 2013). In the "offshore southern seamount fishery", there is a trip limit of one vessel per month from March to September, which is determined by a lottery and each trip has a catch limit of 75,000 lbs. Although bottom longline has been shown to be less destructive than bottom trawls and other gear it is still capable of impacting VMEs (Pham et al. 2014). Under normal use in Canada, bottom longline trap sets are frequently dragged, rolled, and bounced on the seafloor (Gauthier 2017). Further, derelict fishing gear is known to damage underwater habitats such as corals and other benthic fauna (NOAA Marine Debris Program 2015). For example, lost trap gear can sink and get dragged along the seafloor by currents, which damages fragile coral and other organisms in its path.

Process

The goal of systematic conservation planning and trade-off analysis in the NPFC CA is to identify and protect VMEs while minimizing the impact to fisheries or other stakeholders. A proposed general process to achieve this is outlined in Figure 2. The process follows the overall procedure for systematic conservation planning (adapted from McIntosh et al. (2018) and Sarkar & Illoldi-

Range (2010)) and is modeled after the SPRFMO decision-making process. These steps outline the general workflow but it is important to note that the process is iterative where some steps will be revisited or flow into others as needed (Figure 2). Ideally, the process will also be reviewed periodically as new data become available, when there are changes in the environment and distribution of the species of interest, or when objectives evolve.

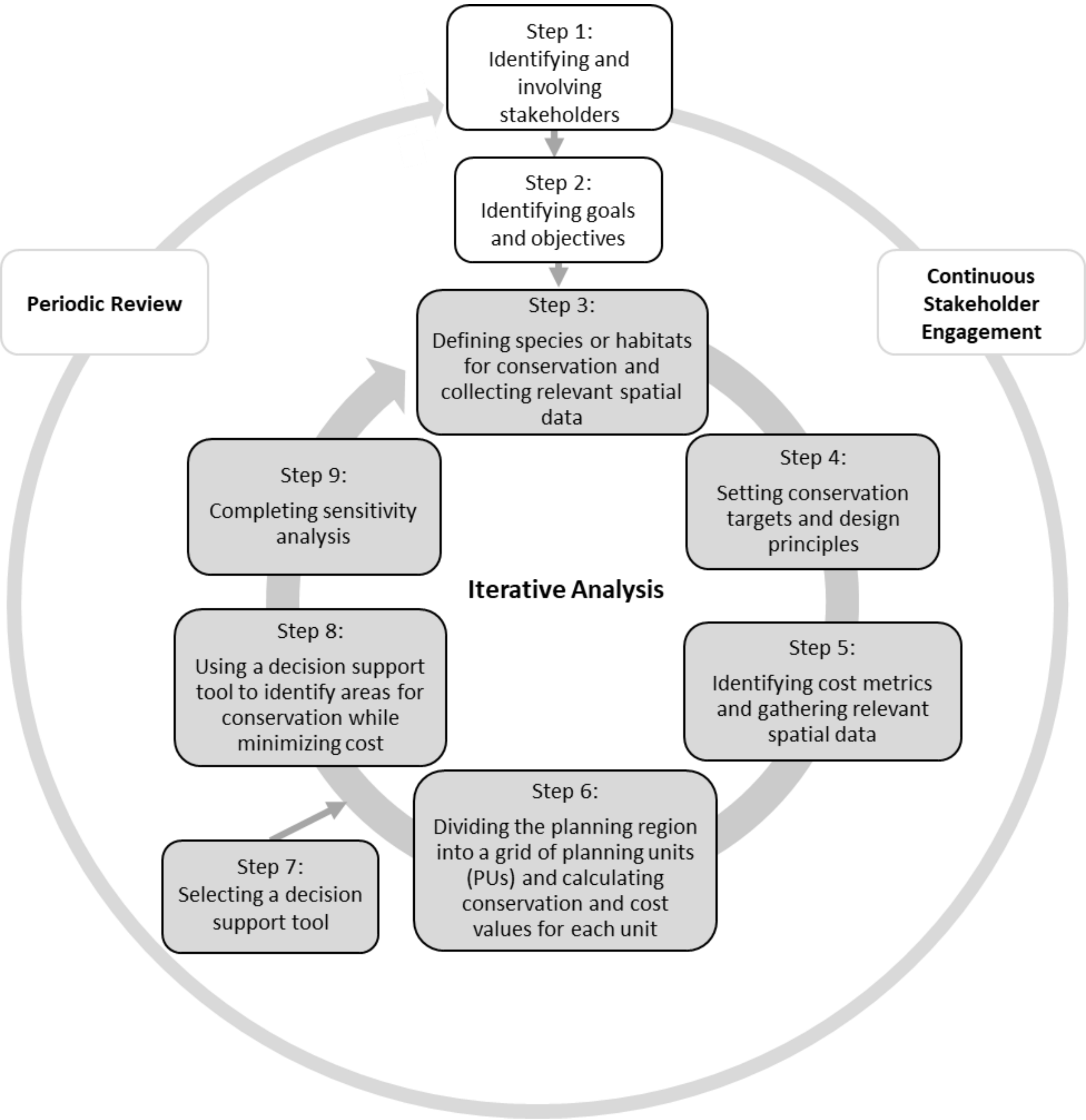

Figure 2. Proposed process for completing trade-off analysis for minimizing impacts to fisheries while protecting VMEs in the NPFC CA.

A brief description of how each step was implemented in the Northeastern Pacific preliminary study is also provided in Table 1 and a more detailed discussion of each step is provided below using Canada's preliminary data from the Northeast Pacific as an example.

Table 1. Quick guide to the trade-off analysis process in the Northeast Pacific preliminary study.

Process	Northeastern NPFC preliminary study
1. Identifying and involving stakeholders	Stakeholders include Canadian commercial Sablefish fishers and possibly environmental non-government organizations (E-NGOs) and First Nations.
2. Identifying goals and objectives	Protect VMEs from SAIs while reducing economic impacts to the Sablefish fishery.
3. Defining species or habitats for conservation and collecting relevant spatial data	Conservation features are based on NPFC's VME indicator taxa which are represented by habitat suitability indices (HSI) values from SDMs.
4. Setting conservation targets and design principles	Conservation targets are based on SDM uncertainty: High certainty = 95% conservation feature area protected Medium certainty = 50% conservation feature area protected Low certainty = 10% conservation feature area protected
5. Identifying cost metrics and gathering relevant spatial data	Economic cost to the Sablefish fishery is represented as landings value and associated fishery data (e.g. location) available from the Canadian commercial fisheries databases.
6. Dividing the planning region into a grid of planning units (PUs) and calculating conservation and cost values for each unit	Square PU grid with a size of 9 km^2 and total of 72,119 PUs is used. - Conservation feature value per PU = mean HSI - Cost value per PU = Sum of landings in kg from the years 2006-2019
7. Selecting a decision support tool	Prioritizr is used to complete the trade-off analysis in this example.
8. Using a decision support tool to identify areas for conservation while minimizing cost	Basic variables are used during analyses in this working paper, but we anticipate additional complexity when this process is applied in collaboration with managers and stakeholders.
9. Completing sensitivity analysis	Many potentially influential factors were examined.

1. Identifying and involving stakeholders

Pomeroy and Rivera-Guieb (2006) provide a holistic definition of stakeholders which includes "Individuals, groups or organizations who are, in one way or another, interested, involved or affected (positively or negatively) by a particular project or action toward resource use." More specifically, stakeholders are affected by management issues because they depend on the managed resources, have claims over the area, and/or conduct activities in the managed area.

A robust stakeholder process that involves all relevant groups and individuals is key in conservation planning. Properly engaging stakeholders is one of the major challenges for successful spatial planning (Frazão Santos et al. 2018). Failure to do so is often due to poor communication, lack of transparency, fragmented government, or the appearance of deliberately biased decision-making. Engagement should be initiated at the earliest planning stages and be consistent throughout the project (Pomeroy & Douvere 2008). There is a range of ways for stakeholders to participate from basic communication to direct engagement in decision making. Stakeholder engagement that involves interactive and proactive approaches such as facilitation, negotiation, and shared decision-making tends to result in more innovative and long-term solutions. Some of the best practices to engaging stakeholders in conservation planning are described by Pomeroy and Douvere (2008) and Vogler et al. (2017) and references therein.

Additionally, stakeholders may have valuable information that is not captured by empirical data. For example, a fishery group can identify areas that are no longer valuable fishing grounds that were once historically fished. This can open areas up for recovery without impacting the fishery. They can also add information to ensure their values are accurately represented, such as a preference for keeping fishing grounds open that are close together to avoid high travelling cost and time.

Preliminary study

The participants in the small Canadian Sablefish fishery are the stakeholders in the Northeast Pacific preliminary study. Connection with the fishery was made early in the process where those involved in developing the trade-off analyses attended fisheries meetings to "listen and learn." The intent during initial introductions was to build connections with Sablefish fishers and managers in 2018. In early 2020, stakeholders and managers were introduced to Canada's potential use of trade-off analysis in the CA at their annual Sablefish meeting with managers. A presentation introduced the fishers to VMEs and Canada's commitment to identifying and protecting them as per the Convention on the Conservation and Management of High Seas Fisheries Resources in the North Pacific Ocean (hereafter referred to as the Convention). During the meeting, the decision-making process of the NPFC was outlined along with its scientific activities including trade-off analysis to protect VMEs. Stakeholders were asked to provide input about specific depths or areas important to the Sablefish fishery, which spatial resolution would be most practical, and other cost indicators that may be important to consider in addition to landings. A few questions regarding concerns of closures and uncertainty with our data were raised. In general, little feedback from stakeholders was provided during that initial meeting.

Sablefish managers were notified about the NPFC scientific meeting in November 2020 and the drafting of this working paper. Managers provided valuable input to this paper, through both discussions and review comments, to ensure the fishers' perspectives were reflected here. The preliminary trade-off analysis team were invited to join the Sablefish fishery meeting again in November 2020. This paper will be sent to fishers prior to the meeting along with some questions regarding the trade-off analysis to allow them time to prepare any input they have.

Other stakeholders to be identified and engaged in this project include First Nations as well as e-NGOs, such as Canadian Parks and Wilderness Society (CPAWS) and the Deep Sea Conservation Coalition (DSCC). Managers and scientists continue to work closely together on the development of an approach for identifying and protecting VMEs while minimizing costs to Canada's bottom fishery in the CA and look forward to engaging stakeholders in the process.

2. Identifying goals and objectives

Clear goals and objectives for systematic conservation planning is essential. This comprehensive planning approach supports diverse goals such as including ecological conservation objectives as well as social-economic objectives. Managers and stakeholders should also be involved in identifying goals and objectives.

Preliminary study
The objectives of the preliminary study in the Northeast Pacific is to identify areas in the study area where VMEs can be protected from SAIs while minimizing the economic impacts to the Sablefish fishery and other stakeholders.

3. Defining conservation features and gathering relevant spatial data

Conservation features are the species, habitat, biodiversity, or ecological components that are the target of conservation within the reserve network. Trade-off analysis can accommodate multiple conservation features. With the context of protecting VMEs from SAIs, conservation features would be spatial data layers representing where SAIs could occur on VMEs. Quantitatively defining VMEs, mapping their distribution, and identifying SAIs is still a work in progress by the NPFC's Scientific Committee. However, structure-forming, cold-water corals are recognized by the NPFC as indicators of potential VMEs which can be used as conservation features. These indicator taxa currently include soft corals (Alcyonacea and Gorgonacea), black corals (Antipatharia), and stony corals (Scleractinia) (NPFC 2019). We recognize that gorgonian corals are now part of the order Alcyonacea following taxonomic revision of the class Anthozoa. In this example, we treat them as part of the same order, although NPFC still recognizes gorgonians as a separate indicator taxon.

Conservation features used in trade-off analyses need to cover the extent of the planning area and can occur as georeferenced observation records, species distribution maps, or habitat maps (Ardron et al. 2010). In many cases, the availability of suitable observation data limits which conservation features can be included. In the absence of site-specific observation records, model predictions of the distributions of VME indicator taxa can be used to identify VMEs and then used in trade-off analyses (e.g. Curtis et al. 2019) as recommended by NPFC Members (NPFC Small Scientific Committee on Vulnerable Marine Ecosystems 2019).

Preliminary study
For the Northeast Pacific preliminary study, the conservation features used in the trade-off analyses was habitat suitability for the VME indicator taxa developed using SDMs as described in Chu et al. (2019). Maximum entropy (MaxEnt) SDMs were developed for each VME indicator taxon using species occurrence records and 30 environmental data layers describing a suite of bathymetric and oceanographic variables at a spatial resolution of 1 km^2. The SDMs provided a habitat suitability index (HSI) map for each VME indicator taxon (Figure 3). HSI generally provides an index representing the capacity of a given area to support the species of interest. Corresponding uncertainty values, standard deviation of multiple model runs (with high standard deviation indicating more uncertainty), were also available and incorporated into the trade-off analyses.

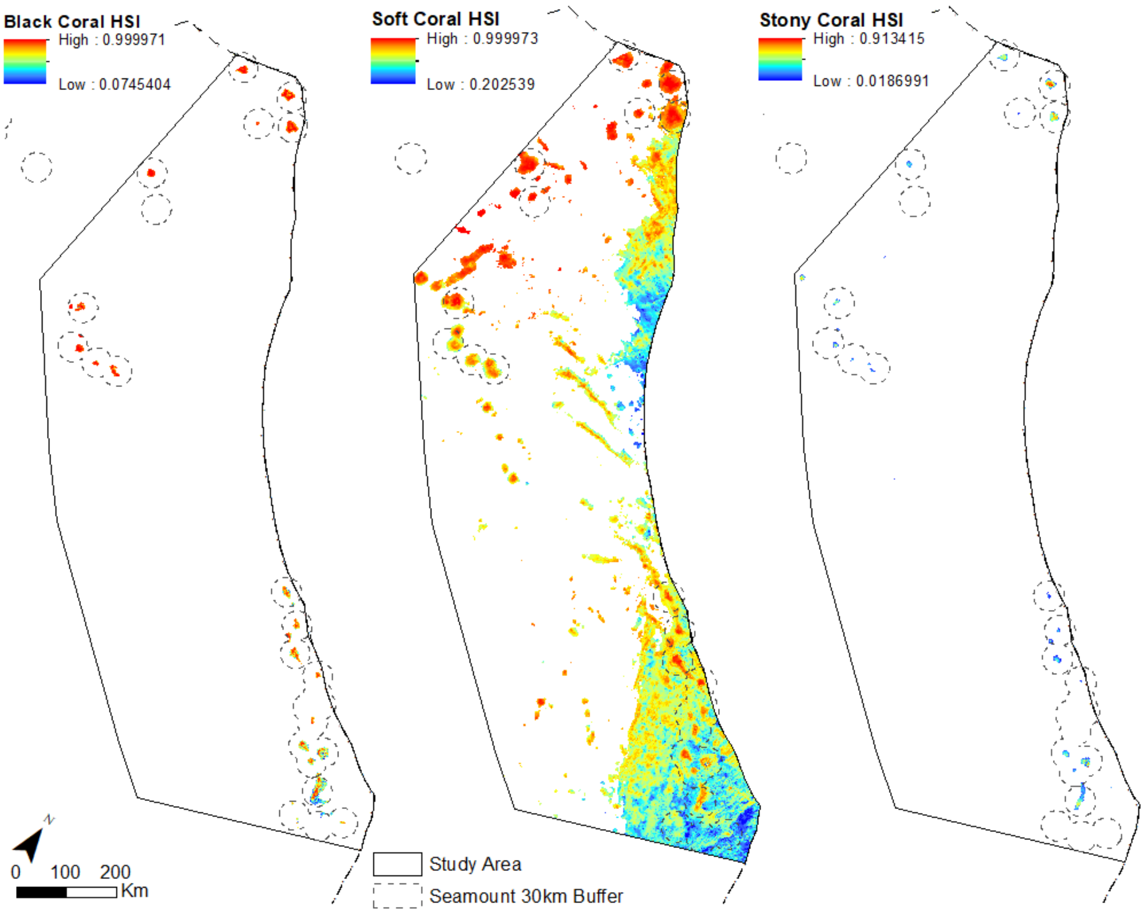

Figure 3. Habitat suitability index (HSI) of VME indicator taxa from Chu et al. (2019) used for conservation features in the Northeast NPFC CA preliminary study trade-off analysis.

Because the conservation feature data for VME indicators are modeled predictive data, model uncertainty has been raised by stakeholders and analysts as an important issue to consider in the trade-off analyses. To address this concern, standard deviation values corresponding to the HSI values were used to categorize predictions into groupings of high, medium, and low certainty. To define uncertainty categories, all standard deviation values were extracted for the study area and quantile breaks were used to define category cutoffs. For the preliminary analysis, quantile breaks of 0.2 and 0.5 were used for each taxon, meaning that the lowest 20 percent of standard deviation values were categorized as high certainty and the highest 50 percent of standard deviation values were categorized as low certainty (Figure 4). These quantile breaks were chosen conservatively to prioritize protection of areas where HSI values are associated with the most certainty. Additional analyses are needed to assess if more suitable uncertainty thresholds should be developed.

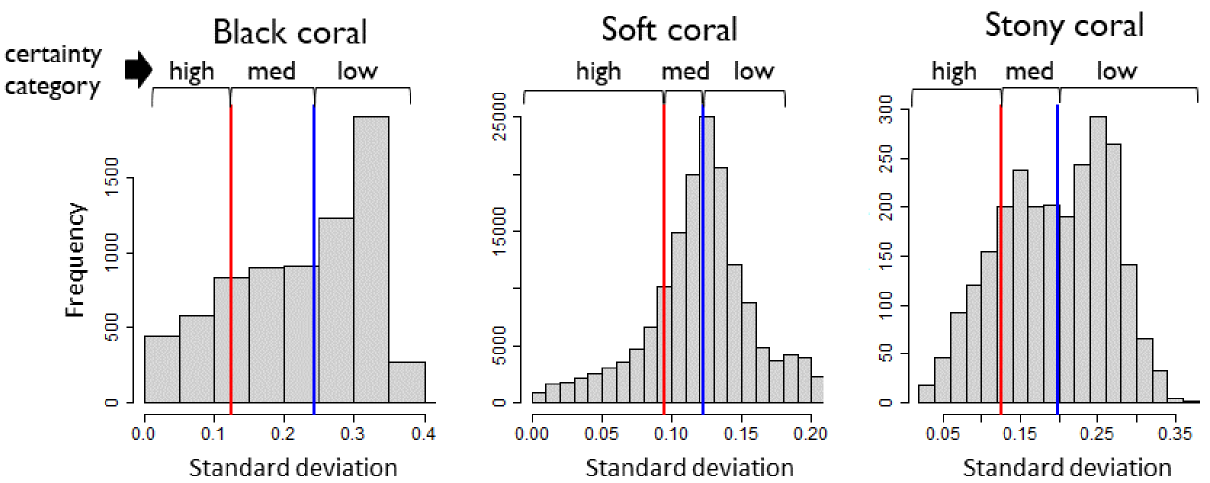

Figure 4. Frequency histograms showing the use of quantile breaks in the HSI standard deviation values to define certainty categories of VME indicator data in the trade-off analysis preliminary study in the Northeast NPFC CA. Standard deviation cutoff values of 0.2 (red – high certainty category cutoff) and 0.5 (blue – low certainty category cutoff) were used for preliminary purposes.

Once HSI values were categorized there was a total of nine conservation features used in the trade-off analysis (three taxa each with three categories). The conservation features were:

- Black coral – high certainty
- Black coral – medium certainty
- Black coral - low certainty
- Soft coral – high certainty
- Soft coral – medium certainty
- Soft coral – low certainty
- Stony coral – high certainty
- Stony coral – medium certainty
- Stony coral – low certainty

4. Setting conservation targets and design principles

Conservation targets specify how much of each conservation feature is to be protected in the final protected area solution. Multiple factors can contribute to identifying conservation targets. For example, conservation status such as the International Union for Conservation of Nature (IUCN) Red List categories and criteria, where higher status would result in higher protection area, or policy such as the CBD Aichi biodiversity target to conserve 10% of coastal and marine areas by 2020 (CBD 2010) and the UN Sustainable Develop Solutions Network Target 14.5 (SDSN 2012). Further, design principles can be set to influence the geographic configuration of the network. For example, network sites should be larger than 20 km^2 or sites should be within a certain distance from each other to facilitate larval dispersal.

The NPFC calls on Members to implement CMMs to protect VMEs from SAIs (see CMM2019-06, NPFC 2019) but no further guidelines are provided on setting conservation targets for VMEs in trade-off analyses. More consideration is needed to define appropriate target levels and this decision-making process should include stakeholders and managers.

Preliminary study
The preliminary study uses a tiered approach to assigning conservation targets. Not only does this allow more flexibility in the trade-off but it incorporates model uncertainty into the analysis. Higher targets were chosen for model predictions that had higher certainty, where 95% of the VME area associated with the high certainty category was set to be conserved and VME areas associated with medium and low certainty data were assigned 50% and 10% conservation targets, respectively (Table 2). We note that our conservation targets are arbitrarily set to illustrate how to incorporate uncertainty into trade-off analyses. Manager and stakeholder input and sensitivity analyses are needed to determine the optimal targets to use when providing advice on VME area protection.

Table 2. List of conservation targets used in the Northeastern NPFC CA preliminary trade-off analysis based on uncertainty categories of habitat suitability index (HSI) values. Note these targets were arbitrarily set by analysts in the preliminary study for example purposes only.

Standard deviation uncertainty category	Conservation target example
High certainty	95%
Medium certainty	50%
Low certainty	10%

5. Identifying cost metrics and gathering relevant spatial data

Cost metrics reflect the non-conservation value of areas and typically represent socioeconomic objectives in trade-off analysis. Ideally, scientists, managers, and stakeholders collaborate to define a quantitative cost metric that reflects the socioeconomic goals. Collaboration at this step would maximize benefits and outcomes that are acceptable to stakeholders.

Like the conservation features, cost metric data must be spatial, quantitative, available in an appropriate resolution, and credible. Such socioeconomic data can be difficult to obtain. In such cases surrogate cost metrics can represent the cost of conservation. For example, the distance to fishing ports can represent cost to fisheries. It is important to note, however, that the quality and representativeness of data used in trade-off analyses can greatly influence the results. For example, incorporating commercial fishing information at a fine-resolution spatial scale can substantially reduce the economic losses compared to analysis based on coarse-resolution data (Richardson et al. 2006).

Preliminary study
Given that one of the objectives in the preliminary study is to minimize economic impacts to the Sablefish fishery, fishery landing values were used as the cost metric. While fishery landings are a commonly used cost metric, stakeholders were asked to provide feedback and input on what cost metrics can best incorporate their values into the analyses. Thus, identifying cost metrics is an iterative process as feedback from managers and stakeholders become available.

Canadian commercial Sablefish fishery landings data was obtained from Fisheries and Oceans Canada (DFO) Fishery Operations System (FOS). This data is a merge of fisher logbooks, which provide set-by-set enumeration of the location and quantity of catch (mix of pieces and weights, depending on species), with a dockside monitoring program which provides the actual weight of each species landed. Position data and 100% monitoring was mandated in 2006 and determined the timeframe of our study. All hook and line trips also have mandatory electronic monitoring (DFO 2020).

Criteria for final data selection include:

- Years: 2006 - 2019
- Target fishery: Sablefish fishery events occurring in our study area
- Species: Any caught and landed species during targeted Sablefish fishing events (releases were removed)
- Catch: Total landings in kilograms

Canadian commercial fisheries data is protected as per Canada's Access to Information Act and Privacy Act. Individual data records are confidential in order to safeguard the competitive position of an individual fish harvester. Therefore, prior to using the data in the trade-off analysis, landings were further filtered to data points where three or more vessels were reporting for a time and area of interest, also known as the "three boat rule". With the intent to share the data, code, and methods in the preliminary study, all fisheries data used and presented in this study have been processed according to confidential data guidelines using the three boat rule. This additional filtering reduced an already sparse dataset and also influenced the planning unit (PU) grid size discussed further on. The spatial resolution of data used in this example is relatively coarse, however, when trade-off analyses are used to provide management advice to Canada and NPFC, analysts will use data at the finest resolution possible to maximize the quality of the results.

Sablefish landings concentrate over several seamounts including Eickleberg, Warwick, Corn, Cobb and Brown Bear Seamounts (Figure 5). The PU cost was calculated as the total sum of landings that occurred within that PU from 2006 - 2019. Landings occurred in only 0.07% of PUs. In PUs where fishing did occur, total landings ranged from 551 kg – 29,559 kg. Figure 6 shows a recent increase in the mean annual landings where mean annual landings from 2017 - 2019 have doubled compared to the long term average from 2006 - 2019. This increase may be a result of closures to fishing on seamounts within Canada's EEZ in 2016 that displaced some of the Sablefish fishing effort to seamounts in the NPFC CA. It may be worth considering using only data from more recent years in the analysis so that cost accurately reflects the current fishing pattern. Such a decision would require discussion among scientists, managers, and stakeholders.

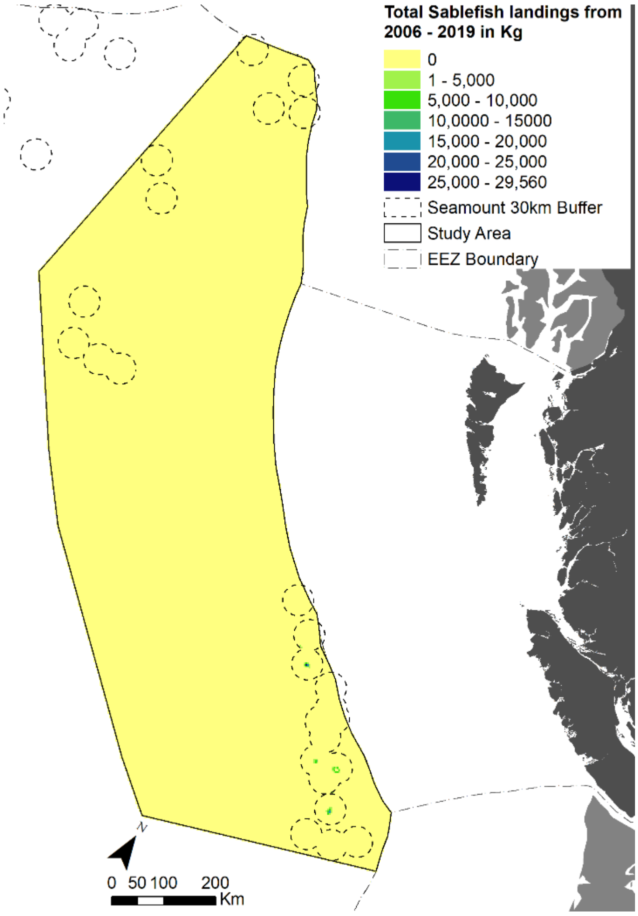

Figure 5. Total landing values in kg for the Canadian Sablefish fishery from 2006-2019 aggregated in 9 km^2 planning units. Data were obtained from Fisheries and Oceans Canada (DFO) Fisheries Operation System (FOS) and have been filtered according to the "three boat rule" for confidentiality purposes.

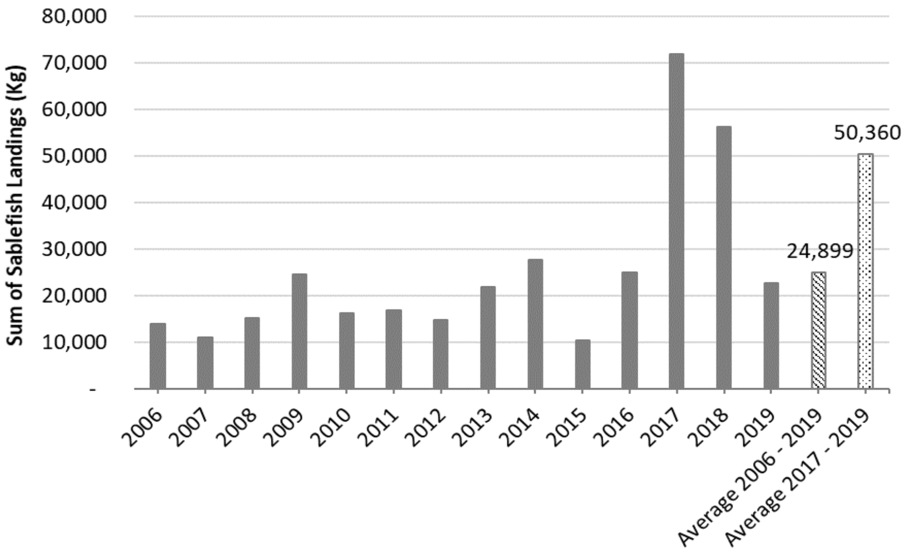

Figure 6. Annual Sablefish landing totals in kg summed over the entire study area. Hashed bar and dotted bar represent the annual mean for long-term (2006-2019) and short-term (2017-2019) records, respectively.

6. Dividing the planning region into a grid of planning units and calculating conservation and cost values

Decision support tools require the planning region be divided into a grid of PUs which can vary in size and number. However, some decision support tools work best with certain PU characteristics. For example, square grids are the most commonly used in Marxan analysis, however, hexagonal grids have shown to be more efficient in creating reserves with low edge to area ratios (Birch et al. 2007). PUs cannot be smaller than the resolution of the input data. Higher numbers of PUs generally affect processing time which can be a limiting factor with some decision support tools. Marxan, for example, recommends a maximum of 50,000 PUs while prioritizr is capable of working with over a million within reasonable computational processing times. The size and number of PUs used will be determined by the input data resolution, study area size, and decision support tool used.

Preliminary study
The PUs used in the Northeastern NPFC CA preliminary study was a square grid with a size of 9 km^2 (i.e. 3 km x 3 km) created using ArcGIS software (ESRI 2019). This resulted in a total of 72,119 PUs. It was preferable to use 1 km^2 PUs aligned with the conservation feature raster data given that the decision support tool used, prioritizr, is capable of handling high numbers of PUs. However, the confidentiality three boat rule processing resulted in a high amount of data lost with smaller PU sizes. After some sensitivity analysis, we found that 9 km^2 created an acceptable balance of retaining data while preserving spatial resolution in our preliminary study. Square units were chosen over hexagonal ones so that they could be more easily aligned with input data raster cells. This also simplified calculating the PU conservation feature values.

The conservation feature values for each planning unit was the mean HSI from SDMs for VME indicator taxa Alcyonacea, Antipatharia, and Scleractinia. The PU grid aligned exactly with the conservation feature raster cells so that each PU covered nine HSI raster cells.

The cost value for each PU was the sum of observed landings, ranging from 0 kg – 29,559 kg. Since each PU must include a cost value greater than zero, a constant of 1% of the highest PU cost was added to every PU. The greater the range in social-economic cost values the more certainty there is that PUs with higher fisheries landings would be selected for protection over PUs with no landings, which can be influenced by the constant used. Further sensitivity analysis is needed to assess the effect of different constants.

7. Selecting a decision support tool

There are a number of decision support tools available that use different approaches for measuring conservation value and selecting conservation areas. The most widely known tools used in marine spatial planning include Marxan/MarZones, SeaSketch, Zonation and InVEST (Janßen et al. 2019). A more recently available tool, prioritizr (Hanson et al. 2020), holds promise as a similar tool to Marxan without some of the drawbacks such as poor processing performance (Schuster et al. 2020). A study comparing Marxan and Zonation analysis found the results were not greatly affected by the software package used (Delavenne et al. 2012) and suggests the software package should be chosen based on the project objectives and additional functionality and strengths of the different tools. Another factor to consider is the level of documentation and support associated with different decision support tools and expertise required to use them.

One of the main differences among these tools is the objective it focuses on. Both Marxan and prioritizr's objective is to meet conservation targets, such as protecting a percentage of VME areas, while minimizing the social-economic and management costs (Table 3). In contrast, Zonation's objective is to maximize biodiversity benefits given a fixed cost. However, Zonation is capable of supporting target-based planning with some modification (Moilanen 2007). Another large difference among the tools is the algorithm used to complete the analysis. Marxan and Zonation both use simulated annealing, while prioritizr uses integer linear programming. Integer linear programming outperforms simulated annealing methods in terms of processing time and ability to minimize socioeconomic cost. Schuster et al. (2020) found that solutions using integer linear programming algorithms resulted in 12-30% lower socioeconomic cost and were 1,071 times faster than using simulated annealing. Prioritizr has yet to be tested on many complex problems because it has only been available to the greater marine spatial planning community since 2016. In comparison, Marxan has been applied for two decades, is the most widely used decision support tool for marine spatial planning, and has been thoroughly tested on large scale and complex problems in marine environments. Scientists, managers, and stakeholders should work together to select one or more software packages to support decisions on marine spatial planning, including VME area protection.

Preliminary study
Prioritizr was used as the decision support tool for the preliminary study, in part so that the filtered data and code could be shared with NPFC Members, and also because the software is free and provides a single optimal solution. Prioritizr provides a very similar analysis to Marxan (Schuster et al. 2020) but is run using the free programming software R (R Core Team 2020). Visualization of the results can be done in R which reduces the need for additional spatial analysis software, such as ArcGIS. The data inputs can be formatted using the same criteria as Marxan which makes it easy to transfer a project between Marxan and prioritizr.

An attractive feature of prioritizr is its ability to share reproducible results. Currently, the analysis needs to be coded in R which results in scripts being shareable and analyses being quick and easy to reproduce. In addition, a R Shiny interface is in development that would allow a point and click browser interface, so knowledge of coding would be unnecessary. The vision is for a novice stakeholder to be able to devise a high-quality, data-driven spatial plan in a short timeframe (less than an hour). Some other benefits of prioritizr include:

- Does not require calibration, which is a time intensive and somewhat subjective process in Marxan.
- Superior reproducibility and transparency as only one optimal solution is provided (rather than many near optimal solutions like Marxan) and the same input data provide the same results over and over.
- Excellent documentation and many community resources are available (e.g. stackoverflow.com, tutorials, blogs, mailing lists, etc.).
- A diverse feature package where many functions are available to incorporate different variables and constraints in the analysis such as connectivity, multiple zones, etc. and more can be developed.
- Portfolios can generate a range of solutions to provide decision-makers with options (similar to Marxan).

Table 3. Basic comparison of several decision support tools and their applications.
**This is a high-level summary of these tools and applications. An in-depth literature search would likely reveal more differences and applications.*

	Marxan	**Zonation**	**Prioritizr**
Objective	• Uses a minimum set framework, where the goal is to achieve minimum representation of conservation features based on user defined targets while minimizing socioeconomic cost	• Uses a maximum coverage framework that identifies ranked priority conservation areas given a fixed budget (however, it can still support target-based planning)	• Solves target-based reserve selection problems.
Analysis method	• Simulated annealing algorithm • Stochastic • Operates on polygon vector data	• Simulated annealing algorithm • Deterministic • Operates on large raster data	• Integer linear programming algorithm guarantees optimality and produces lower cost solutions much faster
Outputs/ results	• Produces a range of optimal solutions for the minimum set coverage problem showing areas that satisfy the conservation targets with minimum cost	• Produces a balanced priority ranking and shows a range of conservation investment possibilities rather than a result for one set target	• Produces a single best solution and can be programed to show a range of solutions similar to Marxan.
Applications	• Most commonly utilized software for conservation planning, especially in the marine field	• Mainly terrestrial questions and applications to date	• A newer software with limited published applications to date
Other functionalities	• Requires “Marxan Connect” to account for connectivity • Tends to produce more efficient solutions than zonation • Can incorporate different types of conservation zones with Marxan with Zones • Recommended using only a maximum of 50,000 planning units	• Directly incorporates connectivity • Can only account for one type of conservation zone	• Can account for single or multiple conservation zones • Much faster processing time means you can run in real time or on global databases • Reproducible results given a single best solution • Can analyze problems using over one million PUs

8. Completing analysis using the decision support tool

Completing the trade-off analysis is an iterative process and can be guided by experts, manuals, documentation, and further training.

Preliminary study

Prioritizr offers many options and functions which are well documented to help customize planning problems. The preliminary study focused on using the main basic functions on which more complexity can easily be added in the future. The main prioritizr functions are described in Table 4 along with the function options used in the preliminary study. The full analysis code and how to download preliminary data is available in Appendix A.

Table 4. Eight main function types used in priortizr analysis and summary of the function settings used in the Northeastern NPFC CA preliminary study. This summary is based on functions described at https://cran.r-project.org/web/packages/prioritizr/vignettes/prioritizr.html#initialize-a-problem

Prioritizr function	Description	Preliminary study setting
Loading data and initializing a problem	There are many different ways to initialize a problem depending on the format of the input data.	Data was loaded as a single large spatial polygons data frame from a shapefile attribute table created in ArcGIS and used the corresponding initialization set up for this type of data.
Objective	Used to specify the overall goal of the planning problem.	Minimum set objective ensures that all targets are met while minimizing the cost of the solution.
Targets	How much of each feature is desired or required to be conserved.	Relative targets set the proportion of the total amount of each feature in a study area. A tiered approach was used to include conservation feature model uncertainty.
Constraints	Ensures that solutions exhibit specific properties such as selecting specific PUs for protection.	None were used in our preliminary study but could be used if existing reserves overlapped the study area.
Penalties	Penalize solutions according to specific metrics.	Boundary penalties were used to penalize solutions that are extremely fragmented and create areas that are large enough to ease enforceability.
Decision types	Specify the nature of the decision.	Binary decisions are the default decision-type where PUs are either selected or not selected.
Solver	Specify the optimization software used to solve the problem.	SYMPHONY (Ralphs et al. 2019) is an open source integer programming solver and used in this analysis. Gurobi commercial solver (Gurobi Optimization Inc. 2017) is strongly recommended due to its speed but is not freely available.

The preliminary trade-off analysis was conducted in R and required installation of the R package "prioritizr" (Hanson et al. 2020) and "Rsymphony" (Harter et al. 2017). Planning unit, conservation feature, and cost data were input in the form of a single large spatial polygons data frame from a shapefile attribute table created in ArcGIS.

The analyst conducting the preliminary study trade-off analysis received formal training in both Marxan software and prioritizr (which has very similar principles) at a weeklong course provided by PacMARA. Further, experts were consulted throughout the process to ensure correct application and analysis. The preliminary prioritizr analysis presented here underwent a full review by a prioritizr developer.

9. Completing sensitivity analysis

Sensitivity testing is necessary to ensure the analysis represents the data and addresses the project goals to the best of its ability. Some parameters make large differences in the solutions generated and sensitivity analysis helps identify them so that further analysis can focus on data and parameters that have the largest influence (Ardron et al. 2010). This is a very iterative process where previous steps in the process are revisited. Small changes can be made, for instance to the tool's parameters. Larger changes may be needed, such as including new data that better reflects the socioeconomic or management costs. See in Figure 2 how sensitivity analysis feeds back into previous analysis steps.

Preliminary study

Sensitivity testing was applied to several factors in the preliminary study. Parameters and variables tested include:

- Sablefish landings value including the total sum of landings, mean annual sum of landings, and the natural log transformed mean annual landings.
- Time frame of landings data including long term (2006-2019) versus short term (2014-2019).
- Spatial scales tested included a study area at a local scale focusing on one seamount chain as well as the current study area spanning a larger regional area.
- Conservation feature data type included mean HSI versus HSI presence/absence based on HSI threshold analysis.
- The effect of individual conservation features to show how each VME indicator taxon influences the result.
- Varying conservation targets, in this case, the influence of targets ranging from 10-95%.
- Penalty factors tested include a wide range to see how the spatial fragmentation changed.

The landings values tested include the total sum of landings compared to the mean annual sum of landings. In addition, a natural log transformation of the mean annual sum was examined. In general, the protected area solutions differed according to fragmentation, total area covered, and landings displaced. The consulted experts advised against using transformed cost data as it unnecessarily adds complexity to interpreting the results. The total sum of landings has a much larger value range which can lead to a stronger emphasis on avoiding high fishing areas. However, the mean annual sum of landings may provide a more realistic representation of important fishing areas. It is likely more valuable for the fishery to preserve fishing grounds that are consistently fished with high landings, rather than areas that had very high catches in some years, but not consistently. Further input from fishers is needed to ensure the cost best represents their values.

In terms of the time frame of the landings data used, short-term landing records (2014-2019) resulted in higher fishing displacement compared to using long-term records (2006-2019). This is likely a result of higher overall landings in more recent years. Therefore, using long-term records may provide a more conservative approach in terms of landings displacement, while short-term records may provide a more accurate estimate of displacement if future landings patterns remain high.

To ensure this process is transferable to varying spatial scales in other areas of the NPFC CA, trade-off analysis was also completed on a smaller scale focused on the seamount chain where Cobb, Eickelberg, Warwick, and Brown Bear Seamounts are located (CBD's EBSA 8 in the North Pacific Ocean, see CBD 2014). According to expert advice, the best application of decision support tools is when the conservation features and socioeconomic costs overlap spatially. When we scaled up to a larger region the fishery cost values covered a very small footprint of the study area and had limited overlap with the conservation features. However, the analysis provides valid results at both scales as it accurately represents the conservation and socioeconomic values in the area of interest.

VME indicator conservation feature data was available as HSI values as well as predicted habitat presence-absence based on a calculated threshold (Chu et al. 2019). Using the presence or absence of predicted suitable habitat helped ensure that only highly suitable habitats were counted toward the protected area. However, using the HSI values provides more flexibility in the solutions. With the input of expert consultation, HSI uncertainty categories were developed so that all data could be used to inform the analysis but it is balanced by the use of uncertainty categories.

A wide range of conservation targets were tested. In general, displaced landings increased with increasing conservation targets, although not proportionally. Conservation targets as high as 10% could be assigned with very little impact to the Sablefish fishery. More work is needed to refine the conservation targets assigned to uncertainty categories. Setting conservation targets is a critical decision that requires further management and stakeholder input.

Boundary penalties in the analysis control how compact or fragmented the protected area solution is. This is an important parameter that has implications of practically implementing and enforcing a protected area. Small closures on seamounts would be difficult to assess, difficult to enforce, difficult to model, and may not be operationally feasible for some of the bottom fishing gear that is used in the NPFC CA. However, increasing spatial clustering of the protected area will have trade-offs in economic efficiency where protected areas that have the least impact on the fishery will be the most fragmented ones. This is another opportunity where stakeholder and management engagement would be valuable.

Conclusion

This process for trade-off analysis exemplified in the Northeast NPFC CA preliminary study demonstrates general steps that NPFC Members can take using currently available information to protect VMEs from SAIs. However, this process is not definitive and leaves room for customization based on regional or situational differences among Members. A common thread to aim for is that the process be transparent, inclusive to stakeholders, systematic, and scientifically defensible. As recommended by international organizations such as FAO, The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), and NPFC, uncertainty requires a precautionary, risk-based approach to management.

A team of scientists, managers, and stakeholders to assess the trade-offs between fishing and VME protection can require a lengthy amount of time and considerable resources as it can take a long time to build confidence, agree on objectives, undertake research, and consult (FAO 2019). Further work and discussion around trade-off parameters could aid a consistent application of the process. At a minimum, it is important to agree on conservation targets used since this greatly affects the VME protection outcomes. Additional guidelines for VME protected areas, such as minimum size, connectivity, and fragmentation could be assessed to ensure best practices are followed. Finally, periodically reviewing the trade-off analyses and developing an additional process outlining enforcement, evaluation, and adaptation of identified VME protected areas would ensure their effectiveness persists in practice after implementation.

We look forward to working with managers, stakeholders, and NPFC Members on developing quantitative approaches to identifying VMEs and protecting them from SAIs using trade-off analyses similar to what we describe here.

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Appendix A – Prioritizr code

R code used to complete the Northeastern NPFC preliminary prioritizr analysis is below. The preliminary input data and code is also available at: https://collaboration.npfc.int/node/86

```
######### R code for Prioritizr Northeast NPFC VME Trade-off Analysis Preliminary Study ######
#
# Date: October 2020
# By: Devon Warawa
# Organization: Fisheries and Oceans Canada
# Location: Pacific Biological Station, British Columbia, Canada
# Contact: devon.warawa@dfo-mpo.gc.ca
# Project: NPFC trade-off analysis to protect VMEs from SAIs
#
############ Prioritizr analysis using attribute table from a GIS shapefile ############
# General description:
#  This code uses the prioritizr package to identify areas to protect vulnerable marine
#  ecosystems from significant adverse impacts through a trade-off analysis. The main input is
#  a GIS shapefile containing conservation feature and cost values aggregated by a planning
#  unit grid. The analysis will produce maps indicating the optimal areas for protection based
#  on the data and specified parameters. See https://prioritizr.net/ for a further description
#  of prioritizr and parameters available.
#
# Inputs:
#  The input data must be specified in the script in using the following variables (edit these
#  in section "Specify parameters that depend on the input data" begnning on line 73):
#    - input_shapefile_filename: This is the name of the file that contains conservation
#      feature and cost data aggregated by planning unit. It should be in shapefile format
#      with attribute data saved from a GIS program.
#    - output_filename_prefix: This is the base name used in output files. It should contain a
#      reasonable description of the analysis.
#    - cost_column_name: The column heading that contains the cost values you would like to
#      use in the analysis, such as landing values.
#    - conservation_feature_column_names: Each conservation feature should be in its own
#      column and those column names are specified here.
#
#  Additionally, to configure the analysis you can adjust the following analysis variables
#  which are independent of the input data (edit these in section "Specify parameters that
#  will be varied for prioritizr analysis" beginning on line 96):
#    - conservation_feature_targets: Targets values that specify the amount of conservation
#      features that should be represented in the protected area solution. Relative targets
#      specify the proportion of area of each feature to protect in the study area.
#    - edge_factor: The proportion to scale planning unit edges (or borders) that do not have
#      any neighboring planning units.This helps avoid bias toward choosing planning units
#      near edges. A common factor to use is 0.5.
#    - Penalties: Penalties are used to scale the importance of selecting planning units that
#      are spatially clumped together. Higher penalty values result in more spatial clumping.
#        - penalty_0: Penalty of 0 is usually examined for comparison purposes.
#        - penalty_a, penalty_b, penalty_c: Can be assigned different penalty factors to
#          compare how the solution changes with a range of values.
#
# Outputs will be saved in the same directory that this R code file is saved in. There are
#    two outputs from this script:
#    - One .png image file with a map identifying protected areas for each penalty problem.
#    - One shapefile is saved for each penalty problem ran. The solution_1 column stores the
#      information, where 1 = planning uni tidentified for protection and 0 = not identified
#      for protection in the solution network.
###############################################################################################

# Clear workspace list and graphics.
rm(list=ls())
graphics.off()
```

```r
# Load packages. These may need to be installed before loading.
library(prioritizr)
library(rgdal)
library(raster)
library(rgeos)
library(Rsymphony)
library(GISTools)
library(tmap)
library(shinyjs)
library(tidyr)

# Sets the working directory to the directory this script is stored in.
setwd(dirname(rstudioapi::getSourceEditorContext()$path))

######################### Specify parameters that depend on the input data ###################

# The name of the shapefile that will be read from disk.
input_shapefile_filename = "Prioritizr_Data_Northeastern_NPFC_Tradeoff_Preliminary_Study"

# The prefix to use for the output files.
output_filename_prefix = "Prioritizr_Data_Northeastern_NPFC_Tradeoff_Preliminary_Study"

# cost_column_name specifies the name of the column to use from the loaded shape file for cost
cost_column_name <- "SumKG300"

# Specifies the name of the columns to use as features.
conservation_feature_column_names <- c(
  "BlackLow",
  "BlackMed",
  "BlackHigh",
  "SoftLow",
  "SoftMed",
  "SoftHigh",
  "StonyLow",
  "StonyMed",
  "StonyHigh")

############# Specify parameters that will be varied for prioritizr analysis #################

# Specifies the target for each conservation feature. This problem uses relative targets which
# are a proportion of the maximum area.
# NOTE: The size and ordering of this vector must match the ordering of the columns specified
# in conservation_feature_column_names.
conservation_feature_targets <- c(0.95,0.5,0.1,0.95,0.5,0.1,0.95,0.5,0.1)

# The proportion to scale planning unit edges (or borders) that do not have any neighboring
# planning units.
edge_factor <- 0.5

# This tells the analysis to abort if the specified time limit is exceeded. Enter maximum
# number of seconds.
time_limit_seconds <- 2000

# Assign penalty values for use in prioritizr. Penalty_0 should always = 0 but a,b and c will
# vary according to the data and desired level of clumping. This parameter is similar to the
# BLM in Marxan.
penalty_0 <- 0
penalty_a <- 0.5
penalty_b <- 0.1
penalty_c <- 0.01

#################################### Load data ###############################################

# Load a spatial polygons data frame file that includes all cost and feature data aggregated
```

```
# into planning units. This structure will read an attribute table generated from an ArcGIS
# shapefile. See Prioritizr documentation for using input data in other formats.The result is
# stored in pu_all_data as a SpatialPolygonsDataFrame
pu_all_data <- readOGR(dsn = ".", layer = input_shapefile_filename)

######################### Set up and solve prioritizr problems ###############################

# Calculate the boundary matrix prior to building the problem to improve processing speed.
# The boundary matrix calculates the amount of shared boundary length between different
# planning units.
bm <- boundary_matrix(pu_all_data)

# Create a base prioritizr problem
p_base <- problem(pu_all_data,
  features = conservation_feature_column_names,
  cost_column = cost_column_name) %>%
     add_min_set_objective() %>% # This objective tells the analysis to minimize the cost
                                 # while ensuring targets are met.
     add_relative_targets(conservation_feature_targets) %>% # Targets are set as proportion
                                                            # of the maximum features in the
                                                            # study area.
      add_binary_decisions() %>% # Binary decisions means the analysis will either choose to
                                 # include the planning unit in the solution or not.
     add_rsymphony_solver(time_limit = time_limit_seconds) # Specify that the SYMPHONY
                                                           # software is used. Set solver time
                                                           # limit in seconds.

# Solve problem using penalty_0
p_pen_0 <- p_base %>%
  add_boundary_penalties(penalty = penalty_0, edge_factor = edge_factor, data= bm)
s_pen_0 <- solve(p_pen_0)

## Solve problem using penalty_a
p_pen_a <- p_base %>%
  add_boundary_penalties(penalty = penalty_a, edge_factor = edge_factor, data= bm)
s_pen_a <- solve(p_pen_a)

## Solve problem using penalty_b
p_pen_b <- p_base %>%
  add_boundary_penalties(penalty = penalty_b, edge_factor = edge_factor, data= bm)
s_pen_b <- solve(p_pen_b)

## Solve problem using penalty_c
p_pen_c <- p_base %>%
  add_boundary_penalties(penalty = penalty_c, edge_factor = edge_factor, data= bm)
s_pen_c <- solve(p_pen_c)

################################# Plot solutions using tmap ###################################
palet1 <- c("grey", "blue")

# Plot s_pen_0
map_s_pen_0 = tm_shape(s_pen_0)+
  tm_fill(col = "solution_1",
          title = "MPA = Blue",
          style = "cat",
          palette = palet1)+
  tm_layout(title = paste("Penalty", penalty_0),
            title.size = 1,
            legend.show = TRUE,
            legend.text.size = 1,
            legend.title.size = 1,
            legend.position = c("left","top"),
            frame = FALSE)
```

```
# Plot s_pen_a
map_s_pen_a = tm_shape(s_pen_a)+
  tm_fill(col = "solution_1",
          title = "MPA = Blue",
          style = "cat",
          palette = palet1)+
  tm_layout(title = paste("Penalty", penalty_a),
            title.size = 1,
            legend.show = FALSE,
            legend.text.size = 1,
            legend.title.size = 1,
            frame = FALSE)

# Plot s_pen_b
map_s_pen_b = tm_shape(s_pen_b)+
  tm_fill(col = "solution_1",
          title = "MPA = Blue",
          style = "cat",
          palette = palet1)+
  tm_layout(title = paste("Penalty", penalty_b),
            title.size = 1,
            legend.show = FALSE,
            legend.text.size = 1,
            legend.title.size = 1,
            frame = FALSE)

# Plot s_pen_c
map_s_pen_c = tm_shape(s_pen_c)+
  tm_fill(col = "solution_1",
          title = "MPA = Blue",
          style = "cat",
          palette = palet1)+
  tm_layout(title = paste("Penalty", penalty_c),
            title.size = 1,
            legend.show = FALSE,
            legend.text.size = 1,
            legend.title.size = 1,
            frame = FALSE)

tmap_arrange(map_s_pen_0, map_s_pen_a, map_s_pen_b, map_s_pen_c)

#################################### Save solutions to disk ##################################

# Save the combined solution plot to a PNG file.
png(file= paste(output_filename_prefix, "_Solution.png"))
tmap_arrange(map_s_pen_0, map_s_pen_a, map_s_pen_b, map_s_pen_c)
dev.off()

# Save the solutions to disk.  Outputs a shapefile per problem that was processed for use in
# GIS software.
writeOGR (obj=s_pen_0,
    dsn = "Solution",
    layer = paste(output_filename_prefix, "Solution", "pen", penalty_0, sep="_"),
    driver="ESRI Shapefile",
    overwrite_layer = TRUE)
writeOGR (obj=s_pen_a,
    dsn = "Solution",
    layer = paste(output_filename_prefix, "Solution", "pen", penalty_a, sep="_"),
    driver="ESRI Shapefile",
    overwrite_layer = TRUE)
writeOGR (obj=s_pen_b,
    dsn = "Solution",
    layer = paste(output_filename_prefix, "Solution", "pen", penalty_b, sep="_"),
    driver="ESRI Shapefile",
```

```
    overwrite_layer = TRUE)
writeOGR (obj=s_pen_c,
    dsn = "Solution",
    layer = paste(output_filename_prefix, "Solution", "pen", penalty_c, sep="_"),
    driver="ESRI Shapefile",
    overwrite_layer = TRUE)
```