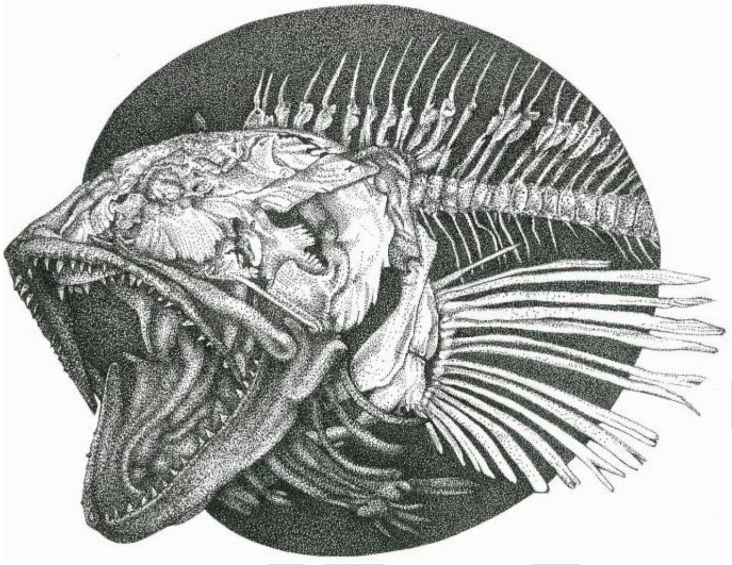
Examination of the Fujioka fishing effects model: model formulation, implementation, and interpretation



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1.0 Introduction

The Fujioka (2006) habitat dynamics model has played a central role in providing information to the North Pacific Fishery Management Council for assessing the impact of commercial fishing gear on essential fish habitat in federal waters of Alaska. The objectives of this briefing are to provide explanations of how the Fujioka model was developed and implemented, collating diffusely spread technical information about the model equations, data inputs, and implementation protocols. Our intent was to write a reference document on the Fujioka model for both technical and non-technical readers. As such, both narrative description of model components as well as mathematical formulae are provided. We provide a suite of footnotes that include additional detail about the model and its implementation; however, the text is standalone without them.

Model simulations and implementation code are provided in the R statistical programming environment language (RDCT 2013). While the original implementation of the Fujioka model for the assessment of commercial fishing impacts on essential fish habitat for the North Pacific Fishery Management Council (USDC 2005) used Matlab (authored by C. Rose et al., National Marine Fisheries Service), we have chosen to migrate the code to R, streamlining in the process. R is freely available, and at present, enjoys wide use amongst fishery analysts. We anticipate no loss in functionality in migrating the National Marine Fishery Service's implementation of the Fujioka model from Matlab to R, and because R is open access, the programming environment is rapidly expanding. R is supported by the

QGIS project (www.qgis.org), an open source and freely available GIS software platform, providing future opportunities to migrate Fujioka model analyses or other essential fish habitat analyses requiring spatially explicit GIS information into a purely open-access environment.

In addition to examination of the Fujioka model and its most recent implementation for the North Pacific Fishery Management Council (USDC 2005), discussion is provided regarding options to expand the functionality of the model by examining the time-path of essential fish habitat under time-varying fishing effort, and to incorporate functional models to relate fishing gear specifications to fishing impact parameters input into the Fujioka (2006) model. Brief discussion of the use of the Fujioka model as a modeling framework to examine non-fishing related impacts and discussion comparing the Fujioka (2006) essential fish habitat fishing impacts model and implementation thereof to the Swept Area Seabed Impact model (SASI) implemented by the New England Fishery Management Council (NEFMC et al. 2011) are also provided.

In what follows, Sections 2.0 and 3.0 provide detailed explanation of the Fujioka model and its implementation during the previous 2005 assessment of fishing impacts on essential fish habitat in Alaska (USDC 2005). The appendix provides streamlined R code that replicates the calculations in the 2005 implementation of the Fujioka-Rose for the North Pacific Fishery Management council. Section 4.0 discusses the Fujioka model as a generic ocean-impacts analysis framework, and Section 5.0 discusses evaluation of alternative management options to minimize adverse impacts of fishing on essential fish habitat with a focus on areal closures and on gear conservation measures (i.e. gear modification to reduce potential impacts to benthic communities). Section 6.0 provides a comparison of the Fujioka model to the SASI model. Finally, Section 7.0 provides recommendations for updating the implementation of the Fujioka model to assess potential adverse impacts on essential fish habitat from commercial fishing gear.

2.0 Description of the Fujioka Model

In the following text, "$\times$" indicates multiplication, and the symbol "$\bullet$" in subscript indexing indicates summation across a given dimension. For example, for $x_{i,j}$ then $x_{\bullet,j} = \sum_i x_{i,j}$.

The "*LEI*" model, or Long-term Effect Index model (Fujioka 2006) was developed originally by Dr. J. Fujioka (National Marine Fisheries, retired), and later implemented by Dr. C. Rose (National Marine Fisheries Service, retired) during the 2005 National Oceanographic and Atmospheric Administration (NOAA) assessment of fishing impacts on essential fish habitat in the Gulf of Alaska, Aleutian Islands and Bering Sea (USDC 2005). This model will be referred to as the Fujioka model during model explanation, and the *LEI* model or the Fujioka-Rose model during implementation discussions.

The Fujioka model translates fishing effort into habitat impacts in a continuous time framework in which model parameters are specified as instantaneous rates (see below). Fishing activity affects habitat through an instantaneous fishing impact rate, a combination of fishing effort and habitat feature sensitivity to fishing activities. In the context of assessing impacts on essential fish habitat associated with fishing (e.g. USDC 2005), fishing activity is generally assumed to be commercial wild capture gear that potentially makes contact with the seabed (e.g. longline skates, trawl gear, and pots). Habitat features are either physical or biological structure or taxa (e.g. epifaunal prey, physical non-living structure) that are believed to be habitat important to commercially utilized marine species. Habitat features are restored to unaffected (or "functional") state based upon instantaneous habitat feature recovery rates. The Fujioka model combines fishing impacts and habitat recovery dynamics into a continuous-time equation that predicts the amount of given habitat feature that persists as unaffected (or recovered) at an instantaneous point in time, t. Importantly, a small error was identified in the habitat effect equations implemented in the 2005 NOAA fishing effects impact assessment (USDC 2005) and was corrected in Fujioka's 2006 Canadian Journal of Fisheries and Aquatic Sciences paper (Fujioka 2006). Below, equations use the corrected forms, following Fujioka (2006) which are different than those outlined in Appendix B of the 2005 Essential Fish Habitat Environmental Impact Statement conducted for the North Pacific Fishery Management Council (USDC 2005); input parameter interpretation remains unchanged between the original and corrected versions of the model. Footnote "**a**" presents additional discussion on potential differences between model output when using the "uncorrected" and "corrected" forms of the Fujioka model equations.

In brief, the Fujioka model uses the calculus of differential equations to develop the key function of interest: amount of impacted habitat in a point in time as a function of fishing effort, habitat feature sensitivity to fishing effort, and habitat feature recovery rates. This occurs by first proposing plausible information about the derivatives of the function of interest, chiefly that the instantaneous rate of change about the amount of pristine essential fish habitat, H, is a balance between the instantaneous rate at which it is degraded by contact with fishing gear and the instantaneous rate at which degraded habitat recovers:

$$ {}^{dH}\!/_{dt} = -IH + \rho h \qquad \text{eq. 1,} $$

where H is the amount of habitat that is unaffected by fishing impacts, h is the amount of habitat affected by fishing impacts (i.e. degraded habitat), I is the fishing impact rate, and ρ is the recovery rate of affected habitat. Note that if recovery rates are very fast (small positive numbers) or if fishing impact rates are very small, then the rate of change of unaffected habitat is very small, and vice versa. The fishing impact rate itself is expressed as the multiplication of f, fishing effort rate, and q, the rate at which fishing-contacted habitat is degraded, or habitat feature sensitivity: $I = fq$. Similarly, the rate at which disturbed habitat is recovered is specified as:

$$ {}^{dh}\!/_{dt} = IH - \rho h \qquad \text{eq. 2.} $$

Using the calculus of differential equations, the propositions about the derivatives specified in Equations 1 and 2 above are solved for the underlying function of interest, i.e. the amount of functional habitat, H, at any point in time:

$$ H(t) = H_0\left[Ie^{-(I+\rho)\times t} + \rho\right]/(I+\rho) \qquad \text{eq. 3,} $$

where H_0 is the initial condition of the system (habitat area) which provides a reference level from which habitat at time t is calculated, and can be viewed as the state of the system under zero perturbation. $H(t)$ from Equation 3 is always less than or equal to H_0, as can be seen by setting the impact rate, I, to zero; $H(t)$approaches zero as the impact rate gets large. For practical purposes in examining habitat dynamics under some system perturbation such as contact with fishing gear, H_0 may be defined as the theoretical maximum possible amount of area of a given habitat, for example as defined by the total amount of suitable substrate type for a habitat feature in the study area (see Section 3.0 below). The appendix of Fujioka 2006 provides the derivation of Equation 3.

With information about the initial conditions of the given habitat feature under no perturbations, H_0, one can calculate the amount of pristine fish habitat remaining at any point in time, however, under the assumptions of constant fishing effort, habitat feature sensitivity, and recovery rates (and relative to H_0). A special case of interest that played a central role in the most recent implementation of the Fujioka-Rose *LEI* model (USDC 2005) is determined by letting time go to infinity, providing the equilibrium level of undisturbed habitat, H_{eq}:

$$H_{eq} = H_0\rho/(I + \rho) \qquad \text{eq. 4.}$$

Implementation of Equation 4 still requires knowledge about the amount of habitat in a given block under no perturbations, but by scaling the reduction by H_0, one can get the relative equilibrium percent reduction in pristine habitat, or the long term effect index *LEI*, as:

$$100 \times \left(1 - {}^{H_{eq}}\!/_{H_0}\right) = 100 \times \left(1 - {}^{\rho}\!/_{(I + \rho)}\right) = 100 \times {}^{I}\!/_{(I + \rho)} = LEI \qquad \text{eq. 5.}$$

LEI ranges from 0%, if $H_{eq} = H_0$, indicating there is no equilibrium loss in functional habitat relative to the pristine state of the system, to 100% if none of the habitat remains in equilibrium ($H_{eq} = 0$). Importantly, *LEI* is an equilibrium percent reduction from whatever amount of habitat existed in a block in an undisturbed state. Thus, an *LEI* of 50% would apply equivalently to an area with initially 20 km^2 of sponges that observes an equilibrium habitat amount of 10 km^2 of sponges under constant fishing, sensitivity, and recovery rates, or an area with initially 2 km^2 of sponges that observes an equilibrium habitat amount of 1 km^2.

While the above models specify habitat reduction under constant (and instantaneous) fishing effort, habitat sensitivity, and habitat recovery, a difference equation is provided in Fujioka (2006) to track the amount of pristine habitat in a block over time under variable fishing effort, i.e. f_t:

$$\begin{aligned} H_{t+1} &= H_t + \left(H_t - \tfrac{H_0\rho}{(qf_t+\rho)}\right)\left(e^{-(qf_t+\rho)} - 1\right) \\ &= H_t + \left(H_t - \tfrac{H_0\rho}{(I_t+\rho)}\right)\left(e^{-(I_t+\rho)} - 1\right) \qquad \text{eq. 6.} \end{aligned}$$

Note that H_0 in Equation 6 is the theoretical maximal pristine habitat amount, and not necessarily habitat conditions at time = 0. The habitat model under variable fishing effort presented in Equation 6 is cast as a difference equation but was derived under instantaneous time. As such, the model presents a continuous time approximation to a true discrete time habitat model. Details regarding the derivation of the difference equation and discussion of the implication of using a continuous time approximation to a discrete time habitat model are presented in footnote "**b**". In short, the model in Equation 6 behaves similarly to a true discrete time difference equation, however, care need be taken to ensure that the input parameters used in an implementation of the variable fishing effort model presented in Equation 6 reflect continuous time (see the paragraphs on "key parameters of the Fujioka model" below). Equation 6 still assumes fixed habitat sensitivity and habitat recovery rates and also requires information about habitat amounts in a pristine, undisturbed state.

Elaborating upon the key parameters of the Fujioka model:

f is the "instantaneous" fishing effort rate measured as the proportion of a model grid block that gets swept (i.e. contacted) by a given fishing gear at a point in time. While the Fujioka model is cast in continuous time and fishing effort specified as an instantaneous rate, previous implementations of the model have assumed an implicit 1-year long fishing season such that f is the proportion of a grid block swept in a year. f = 0.75 would indicate that 75% of the block is swept in a given year. Note, f can be greater than 1.0 if more than the area of a given block is swept by fishing gear over a given time period. The implication of this is that some fish habitat could theoretically be contacted multiple times, although this is probably a rare event based upon historical fishing effort in the Bering Sea, Aleutian Islands, and Gulf of Alaska that indicates that less than 100% of any given model grid block is swept in a year (e.g. USDC 2005). Multiple gear contacts could be interpreted as producing constant proportional reductions in a given habitat feature (see description of q below). Fishing area swept in a grid block is assumed to be distributed uniformly (footnote "**c**") over the entire block. For example, suppose that trawl operators sweep the same 10 km^2 of a 25 km^2 block made up of only sand twice in a season. In this scenario, a total of 20 km^2 of swept area would be incorporated into the model, yielding f = 20/25 = 0.8 for the sand grid block, whereas in reality only 10 km^2/25 km^2 or 0.4 of the block area had been swept by gear (albeit swept twice in this example). Refinements in spatially explicit fishing effort information could improve upon this by defining f as the proportion of a grid block swept by gear one or more times and doing away with the assumption that effort is spread uniformly over an entire block. Furthermore, because during implementations of the Fujioka model the habitat feature sensitivity parameter, q, and the habitat feature recovery parameter, ρ, have been specified with a "continuous" time interpretation (see below), it is recommended that the 1-year discrete time specification of f which has been plausibly estimated as the % area of a grid block swept in a year, which we can denote as f_1, be converted to a continuous time analog using the formula: $f = \ln(1 + f_1)$ (e.g. see Williams et al. 2002, Section 7.2). The change in *LEI* for any given block by going from discrete time "f_1" to continuous time f is generally small except for high fishing effort blocks; however, specification of fishing effort as a continuous rate is recommended for consistency in implementing the continuous time Fujioka fishing effects model. Footnote "**d**" provides example of these discrepancies.

q is habitat feature "sensitivity" to contact by fishing gear. One could view this parameter as a "catchability" coefficient for unaffected habitat. It is measured as the proportion of the extant habitat feature (in a grid block) that is converted to unsuitable, or "unfunctional" fish habitat when contacted by fishing gear. For example, $q = 0.10$ for sponges in response to bottom trawl gear (hypothetical values) would indicate that 10% of the sponge essential fish habitat would be removed by a single contact with trawl gear. q values for the previous Fujioka-Rose implementation of the fishing effects model (USDC 2005) were taken from the relevant scientific literature; in cases where studies described habitat feature reductions after multiple, as opposed to a single, fishing gear contacts, each gear contact was assumed to produce a constant proportionate reduction in a given habitat feature. The single-contact q value used in the model implementation was solved for as:

$\frac{X_{post}}{X_{pre}} = (1-q)^d$ and thus

$$q = 1 - e^{\left(\frac{1}{d}\ln(\frac{X_{post}}{X_{pre}})\right)} \qquad \text{eq. 7}$$

where X_{pre} and X_{post}, are the amount of habitat feature before and after d fishing gear contact disturbances.

$I = fq$ is the fishing-related habitat reduction rate, or the "fishing impact rate". For example, suppose 50% of a grid block composed entirely of sand habitat is swept by bottom trawl gear in a given year ($f_1 = 0.50$ and thus $= \ln(1 + 0.5) = 0.41$) and that 5% of sand habitat is made functionally unavailable as essential fish habitat from one contact with trawl gear (hypothetical value). Then $I = 0.41 \times 0.05 = 0.0205$, or fishing removes available sand habitat at the instantaneous rate of 2.05%.

ρ is the instantaneous rate at which habitat recovers from fishing-related impacts, i.e. the rate at which h transitions to H. The interpretation of ρ as an instantaneous recovery rate is abstract, however, in translating information from the literature on habitat or biological feature recovery rates. In implementing the Fujioka model, ρ is taken as 1 / the expected complete-recovery time for a given habitat or feature (footnote "**e**"). For example, under an implicit one-year time increment, if on average sponges take 1 year to recover from contact with fishing gear (hypothetical value), then ρ= 1.0/1.0 = 1.0, whereas if corals take 10 years to recover from contact with trawl gear (hypothetical value) ρ=1.0/10.0 = 0.1. Similarly, if a sand wave takes 0.5 years to recover from a fishing contact event, then ρ=1/0.5 = 2.0.

Specification of the Fujioka model parameters need match the level of complexity of the information available for a fishing impacts assessment. For example, in the most abstract habitat impact analysis, one could specify a single habitat feature type and single fishery operating in a single contiguous area (e.g. see Section 4.0 and Figure 1 below). In this case, model parameters would include only a single f, q, and ρ parameter. If additional information is available with which to increase the realism of the model, additional parameters may be specified for combinations of habitat features, substrates, and gears, *inter alia*. For example, the 2005 Fujioka-Rose *LEI* implementation (USDC 2005) for the Bering Sea basin included 4 substrate types, 4 habitat features, and 11 gear types along a 5.0 × 5.0 km^2 spatially explicit grid. Habitat feature sensitivity was modeled as specific to a given habitat feature – substrate – fishing gear combination, and habitat recovery rates were modeled as specific to a habitat feature – substrate type combination, necessitating the definition of multiple sensitivity and recovery parameters. Impact dynamics were specified in each 25.0 km^2 block, necessitating habitat feature and substrate distribution information, and fishing effort information for each block (additional detail provided in Section 3.0 below).

3.0 Implementation of the Fujioka model: calculation of LEI habitat effects and habitat effects under time-varying fishing effort

There are numerous possibilities available for implementing the Fujioka model to examine the impacts of fishing on essential fish habitat. For example, analyses could focus on equilibrium proportionate habitat reduction effects under constant fishing effort, habitat feature sensitivity parameters, and habitat feature recovery parameters, as was done during the recent implementation of the Fujioka-Rose model during the National Marine Fisheries Service Environmental Impact Assessment for fishing effects in Alaska (USDC 2005). Alternatively, one could examine habitat impacts along a time-varying effort schedule, for example through implementation of Equation 6 above.

The parameter definitions, and thus the information burden necessary to parameterize a given fishing impacts model, scales with the complexity of the fishing effects analysis. Fishing effort is specified by gear type, and thus for every *G* gear type operating in an ocean area, analysts need specify *G* fishing effort parameters for every spatial block. Similarly, habitat feature sensitivities and recoveries depend on the number of features specified, and inclusion of any interactions between habitat feature, gear type, substrate type, etc… For example, the Fujioka-Rose fishing effects analysis for the North Pacific Fishery Management Council (USDC 2005) specifies for the Bering Sea four habitat features (epifaunal prey, infaunal prey, biological structure, physical structure) and four substrate types (sand, sand/mud, mud, slope), with habitat feature sensitivities specific to a habitat feature – substrate – gear combination (4 habitat features × 4 substrate types × 11 gear types = 176 specifications of q), and recovery parameters specific to a habitat feature – substrate combination (4 habitat features × 4 substrate types = 16 specifications of ρ). The Swept Area Seabed Impact fishing effects analysis implemented by the New England Fishery Management Council further specifies habitat feature sensitivities and recoveries by physical oceanographic energy regime, whereby natural disturbance regimes on benthic biotic communities and physical characteristics are accommodated in assessing the impacts of fishing on fish habitat (NEFMC et al. 2011).

As with the information burden necessary to specify the impact and recovery parameters of a fishing effects model, the substrate and habitat feature distribution data needed to implement a fishing effects analysis also depends on the desired outputs and the complexity of the model. For example, when aggregating across spatial blocks to estimate basin-wide habitat effects during the most recent Fujioka-Rose implementation of fishing effects for the North Pacific Fishery Management Council (USDC 2005), information was needed on the amount of habitat feature present amongst spatial blocks because percent reduction indices are not additive across blocks unless all blocks have the same initial area amount for a given habitat feature – substrate combination or all blocks have the same block-specific *LEI* (which itself would require all blocks observe equivalent fishing effort). To illustrate this point, consider a basin made up only of the following two spatial blocks:

Block 1: initial area of habitat feature *x* = 20.0 km^2, *LEI*=10% given $f_{b1} = 0.1\overline{1}, q = 0.25, \rho = 0.25$
Block 2: initial area of habitat feature *x* = 5.0 km^2, *LEI*=20% given $f_{b2} = 0.25, q = 0.25, \rho = 0.25$

In this scenario, assessment of basin wide *LEI* for habitat feature *x* calculated by simply adding up reduction indices induces an implicit assumption that all blocks have equivalent starting habitat area (equal to 1.0), and leads to 15% basin-wide *LEI* as follows:

$$\sum_{blocks,b} LEI_b \Big/ \sum_b AreaIndex_b = (0.1 + 0.2) \Big/ (1.0 + 1.0) = 15\%.$$

When based upon the actual underlying habitat reduction areas, basin-wide *LEI* is correctly calculated as 12%:

$$\sum_b (LEI_b \times Area_b) \Big/ \sum_b Area_b \quad (10\% \times 20.0 + 20\% \times 5.0) \Big/ (20.0 + 5.0) = 3.0 \big/ 25.0 = 12\%.$$

In the subsequent material in this Section, detailed protocols are provided to implement the Fujioka fishing effects model, outlining data preparation steps, suggested desired output quantities (e.g. as were implemented during the Fujioka-Rose 2005 fishing effects analysis for the North Pacific Fishery Management Council), and implementation algorithms. Two implementation algorithms are outlined: 1) long-term effect index (*LEI*) analysis of fishing effects in equilibrium under constant fishing effort, i.e. as was conducted during the Fujioka-Rose implementation to examine fishing-related impacts on essential fish habitat in Alaska for consideration by the North Pacific Fishery Management Council (USDC 2005), and 2) implementation of the Fujioka model under a time-varying fishing effort schedule (as opposed to fixed fishing effort as imposed under an equilibrium, long-term effect analysis). Appendix 1 provides annotated R code that mirrors the *LEI* analysis under the Fujioka-Rose fishing effects analysis (USDC 2005), using the Bering Sea system as an example. This analysis was originally coded in Matlab by C. Rose (NMFS, retired); to facilitate dissemination of the Fujioka model implementation, the Fujioka-Rose analysis was streamlined and re-coded in R, a freely available and widely-used statistical programming environment currently popular in the natural sciences. The Appendix code document is annotated to explain the steps in the implementation process, and notation matches that outlined below.

3.1 Equilibrium analysis: the Fujioka-Rose (USDC 2005) implementation of the LEI fishing impacts model

In this implementation, long-term equilibrium habitat effects are calculated for a suite of habitat feature – substrate type – fishing gear combinations. The information needs for this implementation are: a) study basin gridded into blocks with knowledge about substrate areas within blocks (biological and physical habitat features are assumed to be uniformly present across a given substrate habitat area within a block), b) fishing effort, which is assumed to be constant for all time, for each block and each fishery, c) habitat feature sensitivity to contact with one pass of a given fishery's gear, and d) habitat feature recovery rates. The following protocol calculates *LEI* for a given habitat feature taking into account both the combined and separate effects of multiple fisheries. The below steps would be repeated for each habitat feature – substrate – fishing gear combination separately, which implies that habitat feature dynamics occur independently of each other; while this may not be appropriate with all taxa and habitat features, information on interactions between fishing-related habitat impacts across habitat features is not presently widely available.

Data collation and input parameter tasks:

> Information required for this implementation includes habitat feature sensitivity parameters specific to each habitat feature – substrate type – fishing gear combination, habitat feature recovery rates specific to each habitat feature – substrate type combination, block-specific fishing effort (assumed to be constant across time), and block-specific substrate area (where it is assumed that habitat features are distributed uniformly across a given substrate type area, see below).
>
> Task 1. Grid the study region space and determine for each block the area of habitat features and of substrate types contained within each block which is used to define H_0 (see comments in Calculation Step 3 below asserting habitat feature distribution when the available information is limited only to substrate area distribution).

Task 2. Calculate constant, fixed fishing effort for each fishery and each block. For example, one may take the average annual amount of a block swept by a given fishing gear over a time period of interest. As recommended in Section 2.0, this annual discrete rate may be translated to an instantaneous rate using the ln(1+annual rate) transformation.

Task 3. Define habitat feature sensitivities. For example, the 2005 Fujioka-Rose implementation (USDC 2005) asserted one parameter for each combination of fishing gear - habitat feature - substrate type.

Task 4. Define habitat recovery rates. For example, the 2005 Fujioka-Rose implementation (USDC, 2005) asserted recovery rates for each habitat feature - substrate type combination.

Quantities of interest to be calculated in the analysis:

Quantity 1. Total basin-wide and combined across all fisheries aggregate *LEI* reduction in the amount of each habitat feature – substrate area combination, given constant fishing effort, constant feature sensitivity, and constant recovery parameters: $LEI_{\bullet,\bullet,c,s}$.

Quantity 2. Block-specific *LEI* reduction in the amount of each habitat feature across all substrate types and fisheries operating within a block, and given constant fishing effort, feature sensitivity, and feature recovery parameters: $LEI_{b,\bullet,c,\bullet}$.

Quantity 3. Fishery-specific contributions to total basin-wide *LEI* reduction for each habitat feature – substrate area combination (given constant effort, feature sensitivity, and feature recovery parameters): $LEI_{\bullet,g,c,s}$.

LEI calculation steps:

Indexing:
b indexes blocks for *b* = 1,…,*B* blocks (*b* as in <u>b</u>locks)
g indexes fisheries for *g* = 1,…,*G* fisheries (*g* as in <u>g</u>ears)
c indexes habitat features for *c* = 1,…, *C* habitat features (*c* as in habitat <u>c</u>ategory)
s indexes substrate types for *s* = 1,…,*S* substrate types (*s* as in <u>s</u>ubstrate)

Calculation Step 1, fishing impact rates across all fisheries combined: Calculate the fishing impact rates for each block, fishery, habitat feature, and substrate combination, $I_{b,g,c,s}$, by multiplying the fishing effort from each fishery applied within a block, $f_{b,g}$, by the appropriate sensitivity parameter specific to a gear – habitat feature – substrate combination, $q_{g,c,s}$:

$$I_{b,g,c,s} = f_{b,g} \times q_{g,c,s} \quad .$$

Sum the $I_{b,g,c,s}$ rates across all fisheries to get the total impact rate in a given block for a given habitat feature – substrate combination, $I_{b,\bullet,c,s}$:

$$I_{b,\bullet,c,s} = \sum_{g=1}^{G} I_{b,g,c,s} \quad .$$

The quantity $I_{b,\bullet,c,s}$ represents the fishing impact rate combined across all fisheries operating in a given block, and specific to a given habitat feature – substrate type combination (e.g. epifaunal prey on sand substrate).

Calculation Step 2, the *LEI* proportion (versus percentage) for individual blocks and across all fisheries' effort combined: For each block, and for each habitat feature – substrate combination, calculate the long term effect index using Equation 5 from above and using the total fishing impact rate calculated in Calculation Step 1, $I_{b,\bullet,c,s}$ along with the appropriate habitat feature – substrate type recovery rate parameter, $\rho_{c,s}$:

$$LEI_{b,\bullet,c,s} = {I_{b,\bullet,c,s}}\Big/{(I_{b,\bullet,c,s} + \rho_{c,s})} \quad .$$

The quantity $LEI_{b,\bullet,c,s}$ represents a percent reduction in the starting amount of a given habitat feature-substrate combination in block b in equilibrium under constant fishing effort, feature sensitivity, and feature recovery rates, as combined across all fisheries operating in the block.

Calculation Step 3, basin-wide aggregate *LEI* for a given habitat feature summed across all blocks, substrates, and fisheries: In order to calculate an aggregate proportionate reduction long term effect index for a given habitat feature – substrate combination across all blocks and fisheries, $LEI_{\bullet,\bullet,c,s}$, extra steps are required to accommodate the fact that blocks have different initial amounts of habitat feature – substrate area; that is to say, one cannot add up proportionate reductions across blocks and then divide by *B* (except under the extreme scenario where all blocks have the same initial amount of habitat feature – substrate combination area, in which case one can then treat initial habitat amount = 1.0 for all blocks). Instead, the protocol requires knowledge about the amount of habitat feature – substrate area within blocks, a high information burden. Unfortunately, information on the distribution of habitat features across the seascape is not widely available, whereas coarse scale distribution maps of substrate types are feasible to construct, as per the USDC 2005 implementation of the Fujioka-Rose model. Thus, as a second best, information on the amount of substrate area within blocks is calculated and an assumption is made that habitat features are distributed uniformly everywhere on a given substrate type. For example, suppose there are four habitat feature types (infaunal prey, epifaunal prey, biological structure, and nonliving structure) in a given basin, and a given 25.0 km^2 block within the basin is made up of 10.0 km^2 of sand, and 15.0 km^2 of mud. Then the assumed initial amount of habitat feature – substrate combination areas within the block are: {10.0 km^2 infaunal prey - sand, 10.0 km^2 epifaunal prey - sand, 10.0 km^2 biological shelter - sand, 10.0 km^2 nonliving structure - sand} and {15.0 km^2 infaunal prey - mud, 15.0 km^2 epifaunal prey - mud, 15.0 km^2 biological shelter - mud, 15.0 km^2 nonliving structure - mud }.

Step 3a, for each block calculate the long term equilibrium areal reduction in a given habitat feature – substrate combination inclusive of effort from all fisheries, $h_{b,c,s}$, using the initial amount of habitat feature – substrate combination area, $A_{b,c,s}$ (i.e. H_0 from Equations 3-6), and the proportionate $LEI_{b,\bullet,c,s}$ index for the block (inclusive of all fisheries):

$$h_{b,c,s} = LEI_{b,\bullet,c,s} \times A_{b,c,s} \quad .$$

Step 3b [**Quantity 1**], calculate the basin-wide proportionate *LEI* reduction for each habitat feature - substrate combination inclusive of effort from all fisheries, $LEI_{\bullet,\bullet,c,s}$ by dividing the sum of functional habitat lost in equilibrium by the total initial amount of area for each habitat feature – substrate combination:

$$LEI_{\bullet,\bullet,c,s} = {\sum_{b=1}^{B} h_{b,c,s}} \Big/ {A_{\bullet,c,s}}$$

where $A_{\bullet,c,s}$ is the basin-wide amount of a given habitat feature – substrate area combination for a pristine, undisturbed system.

Calculation Step 4 [**Quantity 2**], calculate for each block the proportionate *LEI* reduction for each habitat feature, summing across all substrate types and including effort from all fisheries operating in the block, $LEI_{b,\bullet,c,\bullet}$:

$$LEI_{b,\bullet,c,\bullet} = {\sum_{s=1}^{S} h_{b,c,s}} \Big/ {\sum_{s=1}^{S} A_{b,c,s}} = {h_{b,c,\bullet}} \Big/ {A_{b,c,\bullet}} \quad .$$

The quantity $LEI_{b,\bullet,c,\bullet}$ is useful for mapping the spatial distribution of equilibrium reduction in habitat features across an ocean basin (e.g. Figure B.2-2a in USDC 2005).

Note, in the present situation, where habitat features are assumed to be distributed uniformly across all substrate present, the quantity $A_{b,c,\bullet} = \sum_{s=1}^{S} A_{b,c,s}$ would be equivalent for each habitat feature in a block. For example, under the assumption that habitat features are distributed uniformly over substrate, then a 25.0 km^2 block made up of 15.0 km^2 sand and 10.0 km^2 of mud would contain 25.0 km^2 of epifaunal prey, 25.0 km^2 of infaunal prey, etc… In contrast, under distributional assumptions for habitat features within blocks other than uniform distribution, such as an empirical map of habitat feature distributions or an ecological niche-based model for habitat feature distribution (e.g. Peterson 2001), blocks would exhibit different amounts of pristine-state habitat feature areas.

Calculation Step 5 [**Quantity 3**], fishery-specific contributions to basin-wide *LEI* for a given habitat feature – substrate combination, $LEI_{\bullet,g,c,s}$:

Two points complicate the calculation of the contribution to aggregate LEI from a specific fishery. First, the relationship between fishing effort and *LEI* is nonlinear – for example, the marginal effect of fishing effort diminishes as the fishing effort rate gets large, whereby *LEI* asymptotes at a level of 1.0 (100%) at high fishing effort (see Figure 1 in Fujioka 2006). The implication of this is that a unit of a fishery's effort may have different impact on habitat in isolation as compared to habitat in aggregate with effort from all other fisheries operating in a block. Second, in the 2005 implementation of the Fujioka-Rose model, the sensitivity of habitat features to fishing impacts depends on both substrate type and fishing gear type – a plausible assumption, and one supported by the literature (e.g. Grabowski et al. 2014). Thus, one need account for both fishing effort and the amount of substrate area in calculating a single fishery's contribution to aggregate *LEI* for a given habitat feature – substrate combination.

A plausible way forward that was implemented in the 2005 Fujioka-Rose model, was to weight fishing impact rates by area of substrate and then apportion aggregate *LEI* based upon area-weighted fishery impact rates, as is demonstrated below.

Step 5a, calculate fishery-specific impact rates for each block for each habitat feature – substrate combination, $I_{b,g,c,s}$ (see Calculation Step 1 above), and multiply by the area of a given habitat feature – substrate combination in each block, $A_{b,c,s}$, which we denote as $I^A_{b,g,c,s}$:

$$I^A_{b,g,c,s} = I_{b,g,c,s} \times A_{b,c,s} \quad .$$

Step 5b, aggregate each fishery's area-weighted fishing impact rate across all blocks, $I^A_{\bullet,g,c,s}$:

$$I^A_{\bullet,g,c,s} = \sum_{b=1}^{B} I^A_{b,g,c,s} \quad .$$

Step 5c, for each habitat feature – substrate combination, sum the total pool of area-weighted fishing impact rates, i.e. across blocks and fisheries, $I^A_{\bullet,\bullet,c,s}$:

$$I^A_{\bullet,\bullet,c,s} = \sum_{g=1}^{G} I^A_{\bullet,g,c,s} \quad .$$

Step 5d, finally, determine area-weighted fishing impact rate contribution weights for each specific fishery by dividing each fishery's aggregate area-weighted fishing impact rate for a given habitat feature – substrate combination by the total pool of area-weighted fishing impact rate for the habitat feature – substrate combination. These contribution weights are multiplied by the total *LEI* for the respective habitat feature – substrate combination to give a fishery specific contribution to the equilibrium habitat reduction effect index, $LEI_{\bullet,g,c,s}$:

$$LEI_{\bullet,g,c,s} = {}^{I^A_{\bullet,g,c,s}}\Big/_{I^A_{\bullet,\bullet,c,s}} \times LEI_{\bullet,\bullet,c,s} \quad .$$

As an alternative scheme to examine fishery-specific contributions to *LEI*, a potentially more intuitive approach that more closely reflects the non-linear dynamics of the fishing effects model would be to examine fishery-specific contributions to basin-wide habitat impacts by using a currency of habitat area reduction for single-fisheries as opposed to the more abstract area-weighted fishing impact rates. Footnote "**f**" provides an algorithm for such an implementation along with discussion of differences between the approaches; functionally the two approaches lead to very similar numeric results for low impact rate scenarios, however, larger discrepancies may be expected in scenarios of high fishing effects (i.e. combinations of high fishing effort, high sensitivity, and/or low recovery rates).

3.2 Time-varying fishing effort habitat impacts analysis

In addition to estimating equilibrium effects on habitat under constant fishing effort, Fujioka's fishing impacts model may also be used to examine time paths of fishing effects under a schedule of time-varying fishing effort.

Time-varying fishing impacts dynamics are modeled as a difference equation, where habitat impacts at time $t+1$ are a function of the state of habitat and fishing effort in time t (Equation 6 above; see footnote "**b**"). The choice of time step is up to the analyst, however, an annual time step is convenient for several reasons. Annual time steps are consistent with the seasonal nature of commercial fisheries and the commercial fishing regulatory process such that fishing effort is sensibly calculated in terms of annual effort. Furthermore, empirical fishing impacts studies (e.g. Grabowski et al. 2014 and references therein) are typically conducted on the timescale of one or more years and thus habitat feature recovery rates are based upon an implicit annual time step (also see Section 2.0 above).

The information needed to implement time-varying fishing effects analyses are analogous to those required under the equilibrium analysis with the exception that time series of fishing effort by gear type need be generated for each block. Over short time scales on the order of a decade or less, it may be reasonable to assume that habitat feature sensitivity parameters and recovery parameters remain fixed. Modification of the model to include time varying sensitivity and recovery could be implemented simply by indexing these parameters by time, however, the information burden to define time varying habitat feature sensitivities and recoveries is very high given the paucity of empirical evidence on fishing impacts and the high cost to generate such estimates. Similarly, implicit in implementation of the time-varying fishing impacts model is that the spatial distribution of substrate types and the amount of potential functional habitat in blocks (i.e. the equilibrium amount of pristine habitat feature in a block under no fishing effort) remains fixed over the analysis time period.

In order to assess a time path of potential fishing impacts, habitat systems must start from an initial state defining the distribution of functional fish habitat. One option is to assume that the ecosystem starts in some pristine undisturbed state, such as full functional habitat feature coverage everywhere. Alternatively, one could implement a "burn in" period where some level of fishing effort is asserted and either the time dynamic equation (Equation 6 above) is allowed to run for as many years as is necessary under the prescribed fixed fishing effort until habitat amounts stabilize, as was implemented in the New England Fishery Management Council's SASI fishing impacts assessment (NEFMC et al. 2011), or the long term equilibrium habitat state could be derived analytically using Equation 4 above.

In the remainder of this Section, an algorithm is outlined to implement the Fujioka model of fishing impacts under time varying fishing effort. The implementation scheme follows the structure of the Fujioka-Rose fishing effects analysis (USDC 2005) whereby habitat feature sensitivities are dependent on both substrate type and fishing gear type, where recovery parameters are specific to habitat feature and substrate type, and where habitat features are assumed to be distributed uniformly over a given habitat feature – substrate type combination. Alterations to this implementation method to accommodate additional model structure could easily be made through changes to variable indexing, such as parameterization of habitat feature recovery parameters by substrate type and physical energy regime, as in the SASI approach (NEFMC et al. 2011)

Data collation and input parameter tasks:

Task 1. Grid the study region space and determine for each block the areas of habitat features and substrate type contained within each block in a pristine undisturbed state, and also at time = 0. The amount of substrate type and habitat feature in each block at time = 0 could be some asserted arbitrary amount (e.g. full coverage everywhere), or could be based upon a “burn in” period.

Task 2. Calculate time series of fishing effort for each fishery and each block.

Task 3. Define habitat feature sensitivities.

Task 4. Define habitat feature recovery rates.

Under time-varying fishing effort, analysts may observe the time path of fishing impacts given realized historical fishing amounts. The quantities of interest under time-varying effort are analogous to those under an equilibrium analysis (see above), however, as indexed by time. Because this analysis is time-dynamic, the key quantity of interest is the proportionate reduction in functional fishing habitat at a point in time, R_t. This notation differs from the equilibrium analysis outlined above where the key quantity of interest is a long-term equilibrium proportionate reduction in functional habitat, LEI. As with *LEI*, R_t is relative to H_0, the state of habitat under no perturbations, i.e. the theoretical maximum amount of functional habitat in the system.

Quantities of interest to calculate from the time-varying effort analysis:

Quantity 1. Total basin-wide and combined across all fisheries aggregate proportionate reduction in the amount of each habitat feature – substrate area combination in time step *t* +1: $R_{\bullet,\bullet,c,s,t+1}$.

Quantity 2. Block-specific proportionate reduction in the amount of each habitat feature across all substrate types and fisheries operating within a block in time step *t* +1: $R_{b,\bullet,c,\bullet,t+1}$.

Quantity 3. Fishery-specific contributions to total basin-wide proportionate habitat reduction for each habitat feature – substrate area combination in time step *t* +1: $R_{\bullet,g,c,s,t+1}$.

LEI calculation steps:

Calculation steps for the time-varying analysis are similar to those as for equilibrium analysis, except with the addition of time indexing and resulting in time series of key quantities of interest.

Indexing:
b indexes blocks for *b* = 1,…,*B* blocks (*b* as in blocks)
g indexes fisheries for *g* = 1,…,*G* fisheries (*g* as in gears)
c indexes habitat features for *c* = 1,…, *C* habitat features (*c* as in habitat category)
s indexes substrate types for *s* = 1,…,*S* substrate types (*s* as in substrate)
t indexes time for *t* = 1,…,*T* total time steps

Calculation Step 1, fishing impact rates across all fisheries combined in time step *t*: Calculate the fishing impact rates for each block, fishery, habitat feature, and substrate combination, $I_{b,g,c,s,t}$, by multiplying the fishing effort at time *t* from each fishery applied within a block, $f_{b,g,t}$, by the appropriate sensitivity parameter specific to a gear – habitat feature – substrate combination, $q_{g,c,s}$:

$$I_{b,g,c,s,t} = f_{b,g,t} \times q_{g,c,s} \quad .$$

Sum the $I_{b,g,c,s,t}$ rates across all fisheries to get the total impact rate in a given block for a given habitat feature – substrate combination, $I_{b,\bullet,c,s,t}$:

$$I_{b,\bullet,c,s,t} = \sum_{g=1}^{G} I_{b,g,c,s,t} \quad .$$

The quantity $I_{b,\bullet,c,s,t}$ represents the fishing impact rate combined across all fisheries operating in a given block in time step *t*, and specific to a given habitat feature – substrate type combination (e.g. epifaunal prey on sand substrate).

Calculation Step 2, the state of functional fish habitat in time step *t*+1 (H_{t+1}) for individual blocks and across all fisheries' effort combined: For each block and habitat feature – substrate combination, calculate the state of functional habitat using Equation 6 from above and using the total fishing impact rate calculated in Calculation Step 1 for time *t*, $I_{b,\bullet,c,s,t}$ along with the appropriate habitat feature – substrate type recovery rate parameter, $\rho_{c,s}$:

$$H_{b,\bullet,c,s,t+1} = H_{b,\bullet,c,s,t} + \left(H_{b,\bullet,c,s,t} - \frac{H_{b,c,s,0} \times \rho_{c,s}}{(I_{b,\bullet,c,s,t} + \rho_{c,s})}\right)\left(e^{-(I_{b,\bullet,c,s,t} + \rho_{c,s})} - 1\right) \quad ,$$

where $H_{b,c,s,0}$ is the maximal amount of functional habitat in the study system possible, i.e. as would be observed if the system were undisturbed. As with the Fujioka-Rose implementation, let $H_{b,c,s,0}$ be defined as $A_{b,c,s}$, the block area for habitat feature *c* and substrate type *s*:

$$H_{b,\bullet,c,s,t+1} = H_{b,\bullet,c,s,t} + \left(H_{b,\bullet,c,s,t} - \frac{A_{b,c,s} \times \rho_{c,s}}{(I_{b,\bullet,c,s,t} + \rho_{c,s})}\right)\left(e^{-(I_{b,\bullet,c,s,t} + \rho_{c,s})} - 1\right) \quad .$$

The quantity $H_{b,\bullet,c,s,t+1}$ represents the area of functional habitat at time *t*+1 in block *b* which is dependent on the amount of starting habitat feature – substrate combination in the block for an undisturbed system ($H_{b,c,s,0} = A_{b,c,s}$), the state of habitat in time *t*, the combined effort across all fisheries operating in the block in time step *t*, and on fixed habitat feature sensitivity and recovery rates. Note, $H_{b,c,s,0}$ is not necessarily equivalent to habitat state at time = 0, i.e. the start of the study time period; as indicated above $H_{b,\bullet,c,s,t}$ at time = 0 of the simulation period ($H_{b,\bullet,c,s,t=0}$) could be specified with a variety of values including the amount of functional habitat in an undisturbed system, equilibrium habitat amount expected under some asserted fixed fishing impact rate (and fixed habitat feature sensitivity and recovery rates) as calculated analytically using Fujioka's equation for H_{eq} (Equation 4), or through simulation of a "burn in" period of fishing effort.

Calculation Step 3, aggregate basin-wide proportionate habitat reduction at time *t* + 1 for a given habitat feature summed across all blocks, substrates, and fisheries: See Calculation Step 3 in the equilibrium analysis above for additional detail on aggregating block-level proportionate habitat effects into a basin-wide measure.

Step 3a, for each block calculate the areal reduction in a given habitat feature – substrate combination at time *t* +1 inclusive of effort from all fisheries, $h_{b,c,s,t+1}$:

$$h_{b,c,s,t+1} = H_{b,c,s,0} - H_{b,c,s,t+1} \;,$$

and substituting $A_{b,c,s}$ for $H_{b,c,s,0}$,

$$h_{b,c,s,t+1} = A_{b,c,s} - H_{b,c,s,t+1} \;.$$

Note, *h*, area of affected habitat, is specified relative to the definition of $H_{b,c,s,0}$.

Step 3b [**Quantity 1**], calculate the basin-wide proportionate habitat reduction for each habitat feature – substrate combination at time *t* +1, inclusive of effort from all fisheries, $R_{\bullet,\bullet,c,s,t+1}$, by dividing the sum of functional habitat lost at time *t* +1 by the total initial amount of area for each habitat feature – substrate combination:

$$R_{\bullet,\bullet,c,s,t+1} = {\sum_{b=1}^{B} h_{b,c,s,t+1}} \Big/ {\sum_{b=1}^{B} H_{b,c,s,0}} = {h_{\bullet,c,s,t+1}} \Big/ {H_{\bullet,c,s,0}} \;,$$

Substituting $A_{b,c,s}$ for $H_{b,c,s,0}$,

$$R_{\bullet,\bullet,c,s,t+1} = {\sum_{b=1}^{B} h_{b,c,s,t+1}} \Big/ {\sum_{b=1}^{B} A_{b,c,s}} = {h_{\bullet,c,s,t+1}} \Big/ {A_{\bullet,c,s}} \;.$$

In this formulation, $R_{\bullet,\bullet,c,s,t+1}$ is calculated relative to the theoretical amount of habitat for an undisturbed system ($H_{b,c,s,0} = A_{b,c,s}$); analysts could choose to specify habitat reduction relative to any relevant amount, such as the initial starting conditions for the simulation period at time = 0, $H_{b,c,s,t=0}$. A similar argument follows for Steps 4 and 5, below.

Calculation Step 4 [**Quantity 2**], calculate for each block the proportionate reduction of each habitat feature in time step *t*, summing across all substrate types and including effort from all fisheries operating in the block, $R_{b,\bullet,c,\bullet,t+1}$:

$$R_{b,\bullet,c,\bullet,t+1} = {\sum_{s=1}^{S} h_{b,c,s,t+1}} \Big/ {\sum_{s=1}^{S} H_{b,c,s,0}} = {h_{b,c,\bullet,t+1}} \Big/ {H_{b,c,\bullet,0}} \;,$$

and substituting $A_{b,c,s}$ for $H_{b,c,s,0}$,

$$R_{b,\bullet,c,\bullet,t+1} = {\sum_{s=1}^{S} h_{b,c,s,t+1}} \Big/ {\sum_{s=1}^{S} A_{b,c,s}} = {h_{b,c,\bullet,t+1}} \Big/ {A_{b,c,\bullet}} \;.$$

Calculation Step 5 [**Quantity 3**], fishery-specific contributions to basin-wide proportionate habitat reduction for a given habitat feature – substrate combination in time step *t* + 1, $R_{\bullet,g,c,s,t+1}$: The following scheme to assess fishery-specific contributions to basin-wide habitat reduction departs from the Fujioka-Rose (USDC 2005) methodology and follows recommendations outlined in footnote "**f**" to base calculations upon habitat loss area associated with single-fisheries (as opposed to habitat feature – substrate area-weighted fishing impact rates).

Step 5a, calculate for each block the reduction in habitat area at time *t* + 1 under each fishery's single-fishery impact rate in isolation for a given habitat feature – substrate combination, $h_{b,g,c,s,t+1}$, and substituting $A_{b,c,s}$ for $H_{b,c,s,0}$:

$$H_{b,g,c,s,t+1} = H_{b,g,c,s,t} + \left(H_{b,g,c,s,t} - \frac{A_{b,c,s} \times \rho_{c,s}}{(I_{b,g,c,s,t} + \rho_{c,s})}\right)$$

$$h_{b,g,c,s,t+1} = A_{b,c,s} - H_{b,g,c,s,t+1} \quad .$$

Step 5b, calculate for each fishery the total single-fishery areal reduction for a given habitat feature – substrate type combination at time *t* +1, $h_{\bullet,g,c,s,t+1}$:

$$h_{\bullet,g,c,s,t+1} = \sum_{b=1}^{B} h_{b,g,c,s,t+1} \quad .$$

Step 5c, calculate the basin-wide sum of single-fishery areal habitat reduction across blocks and fisheries for a given habitat feature – substrate combination at time *t* + 1, $h_{\bullet,\bullet,c,s,t+1}$:

$$h_{\bullet,\bullet,c,s,t+1} = \sum_{b=1}^{B} h_{\bullet,g,c,s,t+1} \quad .$$

Step 5d, finally, determine single-fishery areal reduction contribution weights for each specific fishery at time *t* + 1 by dividing each fishery's aggregate single-fishery areal habitat reduction for a given habitat feature – substrate combination by the total pool of single-fishery areal habitat loss for the habitat feature – substrate combination. These contribution weights are multiplied by the total proportionate habitat area reduction for the respective habitat feature – substrate combination to give a fishery specific contribution to total proportionate habitat reduction at time *t* +1, $R_{\bullet,g,c,s,,t+1}$:

$$R_{\bullet,g,c,s,,t+1} = {}^{h_{\bullet,g,c,s,t+1}}\!\Big/\!_{h_{\bullet,\bullet,c,s,t+1}} \times R_{\bullet,\bullet,c,s,t+1} \quad .$$

4.0 The Fujioka model as a generic ocean impact analysis framework

The Fujioka habitat impacts model is specified and presented in the context of commercial fishing gear and its potential impacts on essential fish habitat (e.g. USDC 2005); however, as outlined in Section 2.0 above, the model is a generic mathematical abstraction of reality which could be used to examine impacts from any perturbation on any "habitat" system. To elaborate, the key "state" variables in the Fujioka fishing effects model, *H* and *h*, could represent any form of habitat. As opposed to commercial fishing effort, perturbation, f, could represent dredge mining effort, siltation, or even pollution, *inter alia*. Similarly, the habitat "sensitivity to perturbation" parameters specify the rate at which the state variable transitions from "functional" (i.e H in the Fujioka fishing effects model) to "non-functional" (i.e. h) in response to the perturbation rate.

Habitat sensitivity could be specified as an empirical rate, as was done in the Fujioka fishing effects model, or could be parameterized as a functional response translating perturbation to habitat sensitivity. For example the relationship between habitat sensitivity and a specific perturbation could be represented by a logistic-curve shaped function, itself specified with meaningful parameters which define the shape of the "habitat sensitivity" curve. A similar approach has been implemented in the Swept Area Seabed Impact analysis of fishing impacts on essential fish habitat implemented for the New England Fishery Management Council (NEFMC et al. 2011; see Section 6.0 below), where the relationship between commercial fishing gear specifications and effort are translated into habitat perturbations ("f" in the Fujioka fishing effects model) through a deterministic function. With this approach, analysts can simulate modifications to the agents of perturbation (such as a bottom trawl net) and the resulting habitat loss and recovery dynamics. Similarly to habitat feature sensitivity, habitat recovery parameters can be made specific to any perturbation type, such as the recovery rate of benthic fauna to substrate dredging (Newell et al. 1998).

In contrast to fishing-related impacts where the location of fishing effort remains localized, one potential complication with using the Fujioka model (or any other spatiotemporally explicit habitat impacts model) to examine non-fishing related impacts on essential fish habitat may arise when the habitat perturbation event does not remain localized in space, such as the diffusion of a sediment plume associated with extractive mining on the seabed, plumes associated with offal from seafood processing, or diffusion of pollution from an industrial point source such as an oil and gas well, *inter alia*. In such cases, the information burden to conduct quantitative analyses of the impact of non-fishing relate activities on essential fish habitat would be high, requiring information on the distribution of habitat features as well as information on the distribution dynamics of perturbations which may require complicated support models such as oceanographic circulation models.

While the information needs to implement the Fujioka model to conduct spatiotemporally explicit analyses of non-fishing related activities may be prohibitively high, the model could be used for more specific analyses to understand the impact and recovery dynamics under non-fishing related perturbations. For example, the Fujioka model could be used as an initial hypothesis to understand potential impact and recovery dynamics from a specific perturbation schedule on a target habitat feature such as the effects of seabed mining on cobble habitat that may serve as important nursery habitat for juvenile crab species (e.g. Stoner 2009). To illustrate the idea, consider a hypothetical modeling scenario examining the impact of mineral dredges such as those found in Norton Sound off of Nome, Alaska, on small cobble nearshore habitat. In this hypothetical scenario – where all scenario specifics and asserted parameter values are the opinions of the authors of this report and are not motivated by actual empirical or theoretical examinations – suppose mineral dredges may turnover a nearshore patch of small cobble seabed once every three years, which we could represent as a perturbation schedule of: $\boldsymbol{f} = 1.0, 0.0, 0.0, 1.0, 0.0, 0.0, 1.0, \ldots$ Because dredge mining is locally highly invasive on the benthos (Newell et al. 1998), suppose that small cobble habitat experiences substantial loss of functionality as juvenile crab nursery habitat after experiencing turnover from dredge mining, which we can represent as $q = 0.75$. Finally, suppose the hypothetical habitat system is high energy and experiences natural sediment turnover such that disturbed small cobble habitat recovers completely after 4 years in the absence of dredge disturbance but in the presence of natural oceanographic disturbance, which we can represent as $\rho = \frac{1}{4} = 0.25$ (see Section 2.0 above for explanation of the interpretation of habitat recovery rates). Then using Fujioka's habitat impacts model under time varying perturbations (Equation 6 above; see R code provided in footnote "**d**"), one can examine questions about the time dynamic of perturbation and recovery of small cobble habitat under simulated dredge impacts, such as the effect of faster or slower recovery rates or of changes to habitat sensitivity to dredge (Figure 1).

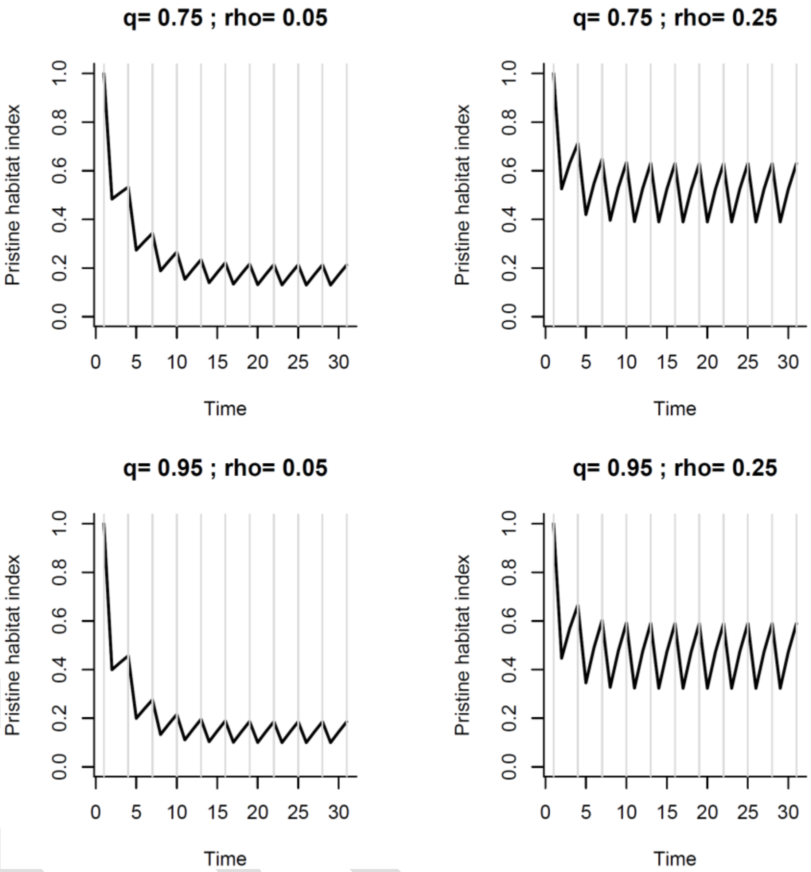

Figure 1. Simulated time dynamics of affected cobble habitat under hypothetical non-fishing related mineral dredge perturbations. In this hypothetical scenario, a single habitat patch is examined, scaled to a habitat area value of 1.0. Habitat dynamics are calculated using Fujioka's time-varying Equation 6 above, and under a perturbation schedule of $\boldsymbol{f} = 1.0, 0.0, 0.0, 1.0 \ldots$, where $f = 1.0$ indicates that the entire habitat area experiences the perturbation. Thin gray vertical lines indicate perturbation events. Different combination of habitat sensitivity to perturbation, q, and habitat recovery rates, ρ, are shown. Note, all parameter value and perturbation schedules are hypothetical and not motivated by empirical or theoretical examinations of the effect of mineral-dredge perturbation on small cobble habitat.

5.0 Evaluating the impacts of alternative management measures on essential fish habitat

There are two key alternative management actions to minimize the potential adverse impacts of commercial fisheries on essential fish habitat to be assessed using the Fujioka model: examination of changes to the magnitude and distribution of fishing effort, i.e. time or area closures, and examination of changes to fishing gear. Time or area closures may be specific to a single type of gear, such as exclusion of bottom trawl from an area (e.g. see Management Alternative 2 to minimize adverse effects of fishing on essential fish habitat in the 2005 NOAA essential fish habitat analysis for the North Pacific Fishery Management Council, USDC 2005), or they may prohibit all fishing gear types, noting the latter may be more extreme but more feasible to enforce (e.g. Sethi and Hilborn 2008).

Analysts wishing to assess closures must decide how to deal with displaced fishing effort (Figure 2). In the most extreme case, one could assume that fishing effort formerly applied in closed areas simply disappears; however, this is unrealistic because many commercial fisheries in Alaska are managed under total allowable catches such that the fleet will continue to fish in open areas to achieve a catch target. Even without management-based catch quotas, fishermen displaced from areal closures are in the business of making profits and thus would be expected to continue fishing in open areas should profitable opportunities be available, i.e. harvest opportunities resulting in revenues net of costs including additional costs associated with fishing outside a closed area which may include travel cost and/or reduced catch rates resulting from competition amongst the fleet or from the distribution of the stock. Theoretically the redistribution of fleet effort could be modeled using understanding about fleet behavior, the distribution of the biological stock, and travel and operating costs (Holland and Sutinen 1999); however, this detail of information is rarely available in commercial fisheries management. Barring information available to predict how effort may redistribute after implementation of a closure, two reasonable schemes would be to reallocate displaced effort evenly amongst the open blocks (Figure 2, middle panel) or perhaps only along blocks adjacent to a closed area (Figure 2, right panel).

no reserve

0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25

even effort redistribution

0.32	0.32	0.32	0.32	0.32	0.32
0.32	▨	▨	▨	▨	0.32
0.32	▨	▨	▨	▨	0.32
0.32	0.32	0.32	0.32	0.32	0.32
0.32	0.32	0.32	0.32	0.32	0.32
0.32	0.32	0.32	0.32	0.32	0.32

edge effort redistribution

0.38	0.38	0.38	0.38	0.38	0.38
0.38	▨	▨	▨	▨	0.38
0.38	▨	▨	▨	▨	0.38
0.38	0.38	0.38	0.38	0.38	0.38
0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25

Figure 2. Effort redistribution schemes under areal closures. Each scenario contains the same total amount of effort equal to 9.0 “ *f* ” units distributed throughout the 6 × 6 block hypothetical study area. The left panel shows the area under no closure. The middle panel exhibits a redistribution of displaced effort from the closure (gray polygon; 8 blocks = 2.0 “ *f* “ units) equally amongst all fished blocks in the study area, whereas the right most panel redistributes displaced effort only to study area blocks adjacent to a closure.

An alternative scheme to reduce the potential adverse impacts of commercial fishing on essential fish habitat is to modify fishing gear to reduce contact with the benthos. For example, commercial fishing gear conservation engineers have explored technology to lift bottom trawl footropes off the seabed floor using bumpers, in an attempt to minimize contact with benthic biological or physical structure but while maintaining catch efficiency (Ryer et al. 2010). Gear conservation alternatives present at least two potentially attractive outcomes. First, fewer location constraints are placed on the commercial fleet, preserving the efficiency of the fleet in terms of travel costs and the ability to target high catch rate areas in harvesting the resource. Second, cumulative biological benefits—as measured as avoided benthic habitat disturbance—across the study region may be large if reductions in fishing gear contact can be reduced everywhere fishing occurs as opposed to specific locations associated with area closures. Additional economic or biological costs may result if gear modifications designed to reduce bottom contact lead to reduced catch rates and thus additional fishing effort to take a target catch quota; however, ultimately, the biological and economic costs and benefits of gear conservation need be analyzed in the context of the costs and benefits of alternative management schemes such as area closures.

Changes to fishing impacts associated with gear modifications could be included in the Fujioka model through either a reduction in fishing effort, f, or a reduction in the sensitivity of habitat features to contact with gear, q, resulting from gear modification. For example, during the 2005 assessment of the impacts of commercial fishing on essential fish habitat for the North Pacific Fishery Management Council, effort data for pelagic trawl fisheries were adjusted by a discount factor to reflect the fact that only a portion of the gear potentially made contact with the seabed during fishing (e.g. Appendix B Table B.2.4 in USDC 2005). The discount rate for pelagic trawl was asserted as an empirically derived quantity; however, as indicated in Section 4.0 above, functional relationships could be developed to explicitly relate gear modifications to a reduction in bottom contact or in the sensitivity of habitat features to contact. An analogous approach has been implemented in the Swept Area Seabed Impact model developed for the New England Fishery Management Council which uses estimates of “contact adjusted” swept area as fishing effort input to the fishing impacts habitat model. The contact adjusted swept area is estimated using nominal contact areas (e.g. trawl tow path), dimensions of a given gear, and parameters relating gear dimensions to bottom contacts (see Section 6.0 “Estimating contact-adjusted area swept” in Appendix D of NEFMC et al. 2011). For example, under this approach, the nominal tow path area of otter trawl gear was decomposed into area swept by ground cables and area swept by the net and footrope, where each gear component is parameterized with an empirically derived contact index, producing a total contact adjusted swept area as a weighted average of the area swept × contact index for the two gear components.

6.0 Comparison of the Fujioka-Rose model with the SASI model

The Swept Area Seabed Impact, or SASI model implemented for the New England Fishery Management council (NEFMC et al. 2011), and the Fujioka fishing effects model implemented for the North Pacific Fishery Management Council have the same key ingredients to assessing the potential adverse impacts of commercial fishing on the essential fish habitat: information on the distribution of habitat types and fishing effort, parameters specifying the sensitivity of habitat types to gear contact, parameters specifying the recovery rate of habitat types after perturbation, and a mathematical model governing the dynamics of a generic habitat system. The implementation of the Fujioka fishing effects and the SASI model were also motivated under the same guiding legislation (Magnuson-Stevens Fishery Conservation and Management Act; USDC 2007) that outlines the requirements for federal management agencies in assessing commercial fishing impacts on essential fish habitat. Thus the two efforts used similar implementation protocols (e.g. including dissemination of model results and interpretation to Council process stakeholders) and examined analogous alternative management actions. As provided under the final Essential Fish Habitat rule under the Magnuson-Stevens Fishery Conservation and Management Act (see NEFMC 2011), the primary requirement of a fishing impacts analysis is to assess whether potential fishing activity impacts on essential fish habitat are “more than minimal and not temporary”. As such, both the Fujioka and SASI fishing impacts models assess only potential adverse impacts of commercial fishing on the benthos, and do not consider the possibility as to whether some benthic disturbances could possibly augment essential fish habitat.

The SASI model and the Fujioka model do differ in some important aspects, and analysts using the Fujioka model may benefit from understanding about alternative approaches to assessing the impacts of fishing activity on essential fish habitat offered in the SASI implementation. The SASI manual prepared for the New England Fishery Management Council (Appendix D in NEFMC et al. 2011) provides extensive detail on the model structure, data inputs, and implementation of the SASI model; for the sake of brevity, only notable differences between the SASI and Fujioka models are provided here. The key differences in the implementation of the SASI model for the New England Council can be summarized into three categories: model structure, information inputs, and model analyses. Each will be discussed in turn.

6.1 Differences between the Fujioka and SASI model structure

The Fujioka model was derived under a framework of continuous time using the calculus of differential equations and a set of simple assumptions about the time dynamics of functional fish habitat under fishing disturbance (see Section 2.0). In contrast, the habitat dynamics equation of the SASI model was directly asserted (as opposed to derived) and was specified explicitly in discrete time. As such, parameter values in the SASI model are in terms of discrete-time sensitivity and recovery dynamics, e.g. based upon annual time steps, whereas Fujioka model parameters need be translated to continuous time (see Section 2.0 above). Furthermore, the SASI model equations are specified in terms of degraded habitat that “decays” to functional state as a function of habitat feature recovery rates and time, whereas the Fujioka model is specified in terms of functional habitat. In practice, this is a trivial difference because under these spatially explicit habitat dynamics, a given model block has a finite amount of total habitat such that block-level degraded habitat can always be translated into units of functional habitat through subtraction: functional habitat area = block area – degraded habitat area.

The transition dynamics of degraded habitat to functional habitat in the SASI model equation is specified as a linear decay function, i.e. a constant proportion of habitat is recovered over each model time step (Equation 5 in Section 8.0 of Appendix D in NEFMC et al. 2011). This differs from the Fujioka model which is cast in continuous time; in this case, a similar assumption about habitat recovery dynamics is made insofar that instantaneous habitat recovery is asserted to be a constant proportion of degraded habitat (i.e. Equation 2 above), which when integrated over continuous time to derive a state equation leads to exponential decay of degraded habitat. As indicated in footnote “**b**”, the practical difference between an explicit discrete time habitat dynamics model specified with a linear decay model for degraded habitat versus the Fujioka continuous time analog is not expected to be great in plausible scenarios of fishing effort, habitat sensitivity, and habitat recovery.

6.2 SASI information inputs

The SASI implementation benefited from relatively fine scale substrate information, and knowledge about the physical processes shaping the distribution of sediments in the Northwest Atlantic study region under jurisdiction of the New England Council (Harris and Stokesbury 2010; Harris et al. 2012). Sediment data were further refined into substrate area maps along an irregular grid using sophisticated spatial analyses based upon Voronoi polygons (e.g. Legendre and Legendre 1998; Section 7.0 of Appendix D in NEFMC et al. 2011).

Reflecting the relatively rich benthic information set available, the SASI implementation specified a larger suite of biological and physical habitat features of interest than was implemented in the 2005 Fujioka-Rose fishing impacts analysis, and further specified habitat features sensitivities and recovery parameters in terms of fishing gear, substrate type, and energy regime. This scheme resulted in 10's of combinations of gear-substrate type-energy regime-habitat feature combination (see Section 4.0 of Appendix D in NEFMC et al. 2011). Similarly to the Fujioka-Rose implementation in Alaskan waters, distributional information on habitat features was unavailable. The SASI approach also used the assumption that habitat features were distributed uniformly everywhere, with the important difference that each substrate type – energy regime combination was specified as being suitable for and thus containing only a subset of the universe of biological and physical habitat features included in the model.

The large number of habitat feature sensitivity and recovery parameters necessitated a substantial amount of information garnered from literature review and expert opinion, which ultimately culminated in an exhaustive review to collate empirical information on fishing effects on benthic communities (Grabowski et al. 2014). In contrast to the Fujioka-Rose implementation where specific values of habitat feature sensitivities and recovery rates were garnered from published literature and used in model runs, the SASI implementation used a combination of published evidence and expert judgment to bin parameter values into a 0,1,2, or 3 scoring scheme. Justification for scoring parameters were recorded, providing transparency to interested stakeholders about the rationale behind parameter values used in subsequent fishing impacts analyses. Binned parameter values were then ultimately transformed to specific quantitative values consistent across bins and parameters. While this approach led to reduced resolution in the parameter values input into the fishing effects analysis, it provided a means to incorporate a diverse range of published and expert information on habitat feature sensitivities and recoveries into a common information framework for input into the quantitative SASI model.

Finally, the core data on fishing activity differed in the SASI implementation insofar that nominal area swept was adjusted (discounted) using functional models to relate commercial gear specifications into a "contact-adjusted" area swept. Under this approach, contact-adjusted swept area is always less than nominal swept area except in the case where commercial gear completely contacts the benthos continuously while fishing (see Section 6.0 of Appendix D in NEFMC et al. 2011). This is in contrast to the Fujioka-Rose implementation where nominal swept area was generally taken to reflect actual bottom contact area, with an exception for pelagic trawl fisheries in which case an adjustment factor was used to discount nominal area swept.

6.3 SASI model analyses

Whereas an analytical solution is available to examine equilibrium effects of commercial fishing on essential fish habitat under the Fujioka (2006) model, which was the only use of the Fujioka model implemented in the 2005 National Marine Fisheries Service analysis for the North Pacific Fishery Management Council, the SASI model is time-explicit and requires simulation to assess long-term effects. Equilibrium analyses of fishing impacts under the SASI implementation were carried out by running the model forward under a fixed fishing effort regime for an arbitrarily long time frame such that model output values (i.e. affected habitat) stabilized, representing long-term equilibrium conditions. Fishing impacts under time varying fishing effort were also carried out in the SASI implementation, and were initiated using a "burn-in" period by first running the SASI model under a fixed fishing effort regime until model output stabilized, and then subsequently asserting a realized time series of fishing effort.

While not specific to the SASI model itself, the New England Council's implementation of the SASI model to assess fishing impacts on essential fish habitat included two additional analyses of interest using SASI model output. First, sophisticated geospatial statistical techniques were used to identify and make inference about "hotspots" of fishing impacts. Local Indicators of Spatial Association (Anselin 1995) analysis was used to identify spatial clusters of fishing under an explicit framework of statistical significance, allowing analysts to assess the uncertainty about hotspot predictions. The Local Indicators of Spatial Association analyses also provided understanding about the characteristics of clusters of impacts, including identification of both "low" and "high" impact clusters (see Section 9.0 of Appendix D in NEFMC et al. 2011).

Second, the SASI implementation included tradeoff analysis examining the interplay between biological and economic outcomes of different alternatives to manage the impact of commercial fishing on essential fish habitat, with a focus on area closures. To reflect the tradeoff decision in a single metric, SASI developers constructed a ratio of the aggregate amount of degraded essential fish habitat (i.e. SASI model output) divided by the net revenues (gross fishing revenues minus variable operating costs measured at the trip level) of a given fishing effort scenario. This ratio metric provided a quantitative performance measure to assess whether area closures, which provide biological benefit in closed areas by removing fishing effort but which lead to a redistribution of fishing effort and potential foregone harvest, lead to a net improvement in system performance relative to a benchmark. Net performance increases with implementation of an area closure would result by observing a sufficiently large biological benefit (reduction in impacted fish habitat) relative to the presumed opportunity cost in terms of fishing production (see Section 10.0 of Appendix D in NEFMC et al. 2011). The SASI benefit ratio metric, termed by the developers as "practicability analysis", provided an objective framework to assess alternative management actions to mitigate adverse impacts of fishing on essential fish habitat, however, the information burden to implement the approach is very high. The method requires all the information necessary to implement a biological fishing impacts analysis such as SASI or the Fujioka fishing impacts model but also information on trip-level commercial fishing operating costs, the latter of which is rarely available with any substantial coverage (but see Tyedmers et al. 2005).

7.0 Recommendation for an updated implementation of the Fujioka-Rose model

The Fujioka (2006) fishing effects model presents a flexible framework for simulating and assessing potential adverse impacts from commercial fishing on essential fish habitat. The Fujioka model, like all mathematical models, is an abstraction of reality and requires substantial information to inform the model. In this Section, we provide a suite of recommendations for subsequent implementations of Fujioka model for Alaskan ocean ecosystems. These include calls for use of updated habitat and effort distribution, and also extensions of the implementation of the Fujioka model including time-varying dynamics and suggestions for opportunities to reflect uncertainty about the parameters that feed into the model. The following recommendations are the opinions of the authors of this report, which were informed through discussion with a range of stakeholders involved in the essential fish habitat impact analysis modeling process for the North Pacific region, including U.S. National Oceanic and Atmospheric Administration staff, Council plan team members, the University research community, and representatives of the commercial fishing industry.

Recommendation 1: Use updated substrate distribution data, providing opportunity to implement additional substrate categories where sufficient data are available in the North Pacific, Aleutian Islands, and Bering Sea regions. Note, while this will improve the biological resolution of the fishing impacts model, it will also require additional information to define parameters related to habitat feature sensitivities and recoveries to accommodate additional substrate categories (see Section 2.0). The extensive literature search undertaken during the development of the SASI model for the New England Fishery Management Council may provide a good starting point from which to identify empirical information relevant to habitat feature sensitivity and recovery rates for North Pacific ecosystems (NEFMC et al. 2011; Grabowski et al. 2014).

Recommendation 2: Use updated commercial fishing effort reflecting fishing seasons up to present.

Recommendation 3: Use the "corrected" versions of the Fujioka model provided in Fujioka (2006) and ensure that all parameters input into the Fujioka model are consistent with the instantaneous time dynamics (versus discrete time dynamics) of the model (see Section 2.0 and footnote "**b**").

Recommendation 4: Develop R code to implement the time-varying fishing effort version of the Fujioka fishing impacts model. The time-varying version of the Fujioka model will allow for insight into the time path for which potential essential fish habitat impacts and recovery occur, such as examining whether fast or slow impact or recovery are expected for habitat feature – substrate type – fishing gear combinations of interest. In addition, under the time varying version of the Fujioka fishing impacts model, analysts could implement schedules of habitat feature sensitivity and recovery parameters to examine outcomes from simulated long term or cyclical trends in ocean conditions that may benefit (or harm) some habitat features, such as changes in water conditions associated with El Nino events (Whitney and Welch 2002) or ocean acidification (Orr et al. 2005).

Recommendation 5: Reflect uncertainty in habitat feature sensitivity and recovery parameters by developing R code for the Fujioka model implementation with option to draw parameter values from statistical distributions centered about analysts beliefs about a given parameter value. Considerable uncertainty will exist in the input data into any fishing effects model, including uncertainty about fishing effort, substrate and habitat feature distribution, sensitivity rates, and recovery rates. To incorporate a portion of this uncertainty, the 2005 Fujioka-Rose implementation (USDC 2005) tested habitat feature sensitivity and recovery parameter values that were a fixed percentage lower and higher than those found from the literature to examine *LEI* levels under systematic changes to input parameters. Alternatively, one could specify probability distributions for sensitivity and recovery parameters and use random draws of parameter values to simulate *LEI* or time-varying fishing effort outcomes. Ranges of outcomes under many different parameter value draws can provide information about the precision of *LEI* or time-varying outcome results under uncertainty about habitat feature sensitivity and recovery rate parameter values.

Recommendation 6: Develop functional or empirical models to relate fishing gear to bottom contact or habitat feature sensitivity rates in order to allow for examination of management alternatives to minimize adverse impacts of commercial fishing on essential fish habitat by simulating changes to commercial fishing gear.

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9.0 Footnotes

[a] The difference between the original Fujioka equations and the corrected equations is that when proposing information about the derivatives of the function of interest, i.e. dH/dt, a term was included to reflect the fact that in an instantaneous point in time, already affected fishing habitat, h, can again be impacted by fishing effort but because it is already degraded, it remains degraded and thus h is not increased by this amount of repeat-impacted extant affected habitat. Thus, in Equation 1 (main text), the equation describing the instantaneous rate of change of pristine habitat, dH/dt, a term equal to e^{-I} was included in the recovery portion of the derivative equation to indicate the recovery only occurs on the proportion of habitat that "survives" repeat impact: $dH/dt = -IH + \rho(e^{-I}h)$. However, as was noted in the publication of the model in Fujioka (2006), the dynamics being specified are in instantaneous time such that the term describing the discount for repeat-impacted affected habitat should be viewed as $he^{-I\Delta t}$, i.e. survival of already impacted habitat from repeated impact is more correctly viewed as over a time interval, which as we are dealing with instantaneous time, $\Delta t \rightarrow 0$ implying that $e^{-I} \rightarrow 1.0$ and drops out, producing the corrected form of Equation 1: $dH/dt = -IH + \rho h$. Note, because the already-impacted habitat discount factor, e^{-I}, was included in the original formulation of the Fujioka model in the derivative equation, the term carries through to all subsequently derived functions, whereas this term drops out of the corrected versions of the models. By comparing the original versus the corrected equations (Table FNA.1), one can see that the inclusion of the e^{-I} term will produce a difference in model output as compared to the corrected equations, particularly if I or ρ are large.

Table FNA.1 Comparison of the uncorrected versus corrected Fujoika habitat impacts equations.

Component	Original (EFH EIS Appendix B)	Corrected (Fujioka 2006)
Rate of change of H, dH/dt	$dH/dt = -IH + \rho(e^{-I}h)$	$dH/dt = -IH + \rho h$
$H(t)$	$H(t) = H_0(Ie^{-(I+\rho e^{-I})t} + \rho e^{-I})/(I + \rho e^{-I})$	$H(t) = H_0(Ie^{-(I+\rho)t} + \rho)/(I + \rho)$
H_{eq} (or H_∞)	$H_{eq} = H_0\rho e^{-I}/(I + \rho e^{-I})$	$H_{eq} = H_0\rho/(I + \rho)$
LEI example 1: $\rho = 1/5 = 0.2$, $f = 5km^2/25km^2 = 0.2$, $q = 0.2$; see note "$"	LEI = 17.23	LEI = 16.67 % difference from original = 3.2%
LEI example 2: $\rho = \frac{1}{2} = 0.5$, $f = 20km^2/25km^2 = 0.8$, $q = 0.4$	LEI = 46.85	LEI = 39.02 % difference from original = 16.7%

[$] R code for LEI calculation function:

```
LEI <- function(f,q,rho){
  LEI.original <- 100*(1-(rho*exp(-q*f)/(q*f + rho*exp(-q*f))) )
  LEI.corrected <- 100*(1-(rho*exp(0)/(q*f + rho*exp(0))) )
  pctchng.original <- 100* abs(LEI.original-LEI.corrected)/LEI.original
  output <- data.frame(f=f,q=q,rho=rho,LEI.original=LEI.original,LEI.corrected=LEI.corrected,PctChnageFromOriginal = pctchng.original)
  }
(LEI(f=20/25,q=.4,rho=.5))
```

[b] The derivation of Equation 6 in the main text above, which is not provided explicitly in Fujioka (2006) is as follows:

Expanding Equation 3 above, we have:

$$H_t = \frac{H_0 I e^{-(I+\rho)t}}{(I+\rho)} + \frac{H_0 \rho}{(I+\rho)} \text{ and } H_{t+1} = \frac{H_0 I e^{-(I+\rho)(t+1)}}{(I+\rho)} + \frac{H_0 \rho}{(I+\rho)}.$$

The difference H_{t+1}-H_t is equal to:

$$(H_{t+1} - H_t) = \frac{H_0 I e^{-(I+\rho)(t+1)} - H_0 I e^{-(I+\rho)t}}{(I+\rho)} = \frac{H_0 I e^{-(I+\rho)t}}{(I+\rho)}[e^{-(I+\rho)} - 1] \;.$$

Noting that $(H_t - \frac{H_0\rho}{(I+\rho)}) = \frac{H_0 I e^{-(I+\rho)t}}{(I+\rho)}$, and replacing constant fishing effort f with variable fishing effort specific to time t, f_t, and thus $I = qf_t$ then we have Equation 6 from the text above:

$$H_{t+1} = H_t + (H_t - \frac{H_0\rho}{(qf_t+\rho)})[e^{-(qf_t+\rho)} - 1] \qquad \text{eq. 6.}$$

Note, while Equation 6 is a difference equation, it is still cast in continuous time and is an approximation to a true discrete time difference equation model. For example, f_t and $f_{t+1}$are still interpreted as instantaneous fishing effort, but abstractly, at two points in instantaneous time, t and $t+1$. Thus, parameterization of Equation 6 need include continuous time rates, and if fishing effort at time $t+1$ is measured as percent of a model grid block swept in year $t+1$ with an implicit annual time step, then the approximation of continuous time rate = ln(1+annual percent swept area) should be implemented (see footnote "**d**" below and description of the fishing effort parameter, f, in the main text).

For comparison, we can propose an explicit discrete time difference equation for the amount of pristine habitat at time $t+1$ that incorporates an annual model time step as:

$$H_{t+1} = H_t + \rho_a(H_0 - H_t) - f_{a,t}qH_t \qquad \text{eq. FNB.1}$$

where ρ_a is the percent recovery of impacted habitat feature over a year, H_0 is the initial amount of habitat feature where it is assumed that the habitat in a given location is such that the area starts from pristine habitat and that no additional habitat feature can be created above what is already present (i.e. H_0 is also the maximum amount of habitat feature in a pristine, undisturbed system), $f_{a,t}$ is the percent of a grid block swept by fishing gear in a year, and q is the proportion of habitat feature that is impacted by a single contact with gear (which has the same interpretation in continuous or discrete time). This simple discrete time difference model for the amount of pristine habitat in a year is similar to the Swept Area Seabed Impact fishing impact model implemented by the New England Fishery Management Council (NEFMC et al. 2011), with the exception that habitat dynamics here are modeled as functional habitat, whereas the Swept Area Seabed Impact model is parameterized in terms of affected habitat.

Results from simulated time series of combinations of effort, habitat feature sensitivity, and recovery rates (Figure FNB.1) demonstrate that the Fujioka approximate discrete time model produces slightly more conservative (less habitat loss) results than the impacts model explicitly specified in discrete time (Equation FNB.1). The differences between the two model habitat impacts are most extreme at combinations of fishing effort, habitat feature sensitivity and recover that produce high loss of functional habitat; however, differences were small or negligible in all cases.

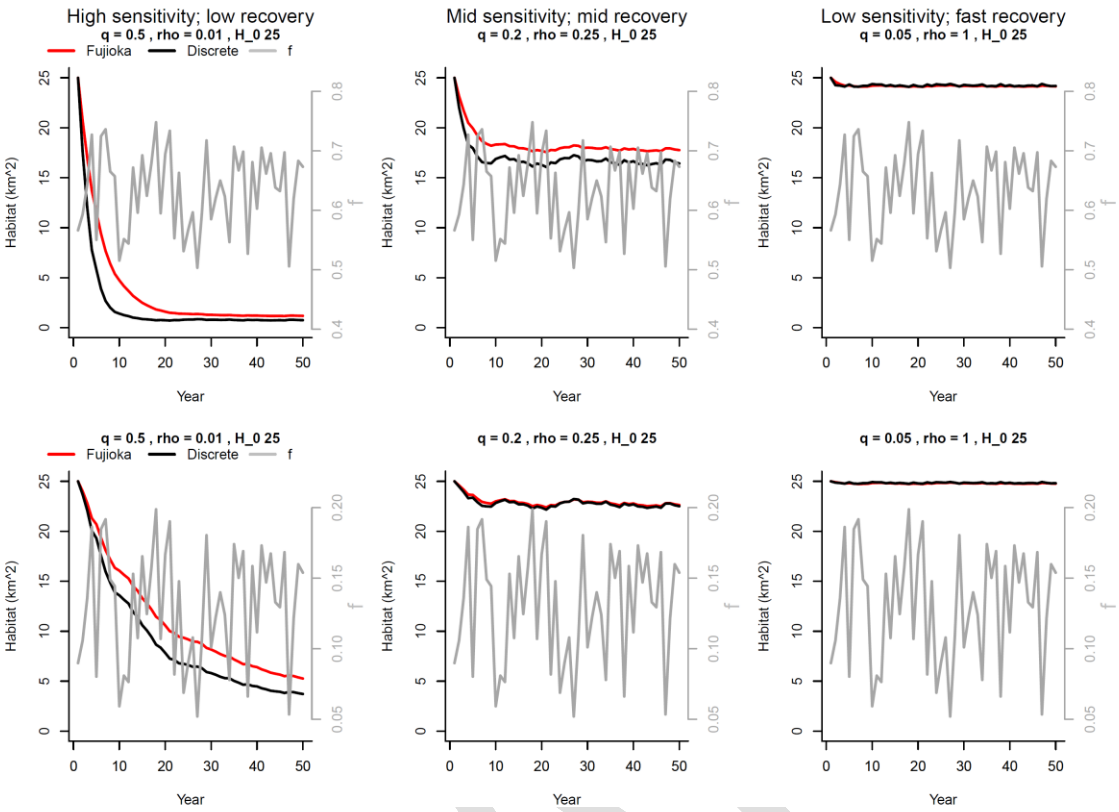

Figure FNB.1 Simulated[‡] habitat dynamics under an explicit discrete habitat impacts model (Equation FNB.1; black lines) or under an approximation to discrete time derived under the continuous time Fujioka model (eq.6 main text; red lines). Gray lines indicate the discrete time fishing effort time series in units of the proportion of a hypothetical 25.0 km^2 block swept by fishing gear in a year. Top rows implement a randomly generated time series of "high" fishing effort (*f* ; same effort time series across all three columns); bottom rows implement a randomly generated time series of "low" fishing effort (same effort time series across all three columns). Columns left to right represent combinations of habitat feature sensitivity (q) and recovery (ρ) that lead to high, moderate, or low fishing impacts given an effort time series. For comparability, discrete time f, q, ρ values have been converted to continuous time equivalents using continuous rate = ln(1+annual rate).

[‡] R code to calculate habitat loss dynamics using Fujioka's approximation to a discrete time model:

```
# Htplus1.FujiokaDiff function, equation 6 from Fujioka (2006), assumes relevant parameters
  # are in instantaneous time (f_t, q, rho).  For example, f_t = ln(1 + % block swept in year t).
  Htplus1.FujiokaDiff <- function(f_t,q,rho,H_0,H_t){
    H_tplus1 <- H_t + (H_t - H_0*rho/(q*f_t+rho)) * (exp(-1*(q*f_t+rho))-1)
    return(H_tplus1)
    } # end Htplus1.FujiokaDiff
```

and the explicit discrete time model:

```
# Htplus1.TrueDiscrete function, asserted difference equation, assumes relevant parameters
  # are in annual time steps.  For example f_t = % block swept in year t.
  Htplus1.TrueDiscrete <- function(f_t,q,rho,H_0,H_t){
    H_tplus1 <- H_t +(H_0-H_t)*rho - H_t*f_t*q
    return(H_tplus1)
    } # end Htplus1.TrueDiscrete
```

[c] This terminology is different than in Fujioka (2006) or in the 2005 Environmental Impact Statement Appendix B (USDC 2005) whereby the distribution of fishing effort is taken to be "randomly" distributed. In reviewing the implementation and specification of the Fujioka-Rose model, we believe "uniformly" distributed more accurately portrays the interpretation of fishing effort and the distribution of habitat or biological features in continuous space.

[d] *LEI* calculated for a given habitat feature in a given block under "f_1" specified implicitly as a 1-year discrete time parameter measured as the percent area of a grid block swept by fishing gear in a year is always greater than *LEI* for the block when fishing effort is converted to a continuous time analog as $f = \ln(1 + f_1)$, as illustrated in Figure FNC.1. The discrepancy becomes greatest at large fishing effort values, e.g. $f_1 > 0.5$, but is small when fishing effort in a block is low (Table FNC.1; Figure FNC.1). Summarizing the implications of implementing the implicit discrete time "f_1" vs. the continuous time analog "f":

- at low to moderate fishing effort, e.g. less than 50% of the area of a block is swept in a year, the difference in *LEI* when using the implicit discrete time "f_1" vs. the continuous time analog "f" is small
- with discrete time f_1, blocks with high fishing effort but highly robust habitat features (i.e. low sensitivity and fast recovery, Figure FNC.1 upper left) or with highly delicate habitat features (i.e. high sensitivity and slow recovery, Figure FNC.1 lower right) have a small positive bias in *LEI* relative to the case where effort measured as percent area swept in a year is converted to a continuous time analog on the order of < 5% *LEI* units (i.e. the long term relative habitat reduction includes an additional 5% reduction, e.g. 50% inflated to 55% *LEI* reduction).
- blocks with high fishing effort but intermediate combinations of habitat resistance to impact and recovery (i.e. either low impact but low recovery or high impact but high recovery) have the highest discrepancies in *LEI* when converting from discrete time effort, f_1 , to the continuous time analog, f; *LEI* discrepancies are on the order of < 15% *LEI* units (i.e. the long term relative habitat reduction includes and additional 15% reduction, e.g. 50% inflated to 65% *LEI* reduction).

Table FNC.1 Differences in discrete time fishing effort, "f_1", and the continuous time analog "f" $= \ln(1 + f_1)$

f_1	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40	1.50
f	0.10	0.18	0.26	0.34	0.41	0.47	0.53	0.59	0.64	0.69	0.74	0.79	0.83	0.88	0.92

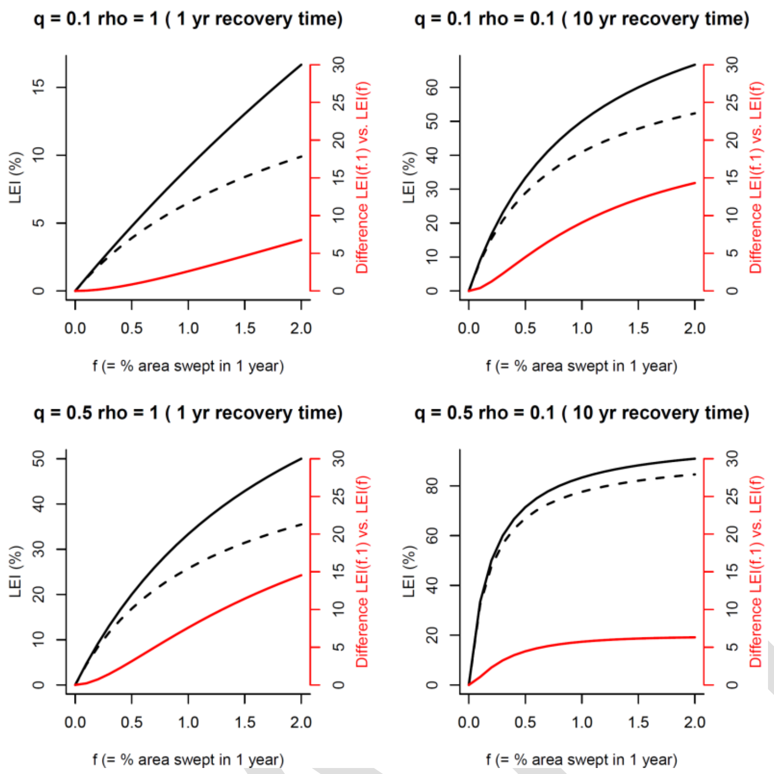

Figure FNC.1 Differences (red lines) in *LEI* when treating fishing effort implicitly as a discrete time value measured as the percent of grid block area swept in a year ("f_1"; solid black lines) versus the continuous time analog ("f" $= \ln(1 + f_1)$; dashed black line). Upper left: “robust habitat” with low sensitivity and fast recovery. Lower right: “delicate habitat” with high sensitivity and slow recovery.

[e] The interpretation of ρ as the average recovery time can be derived by viewing affected habitat, h, as decaying exponentially, i.e. $dh/dt = ke^{-\rho t}$ where ρ is the rate of decay of affected habitat, or alternatively, the rate of recovery to unaffected habitat, and k is a constant (e.g. $k = h_0$ when defining h as h_0 at $t = 0$). In this case, standard derivations of expected lifetimes of processes following exponential decay--such as the lifetime of an electrical component until failure-- show that the mean lifetime for an entity to failure (or conversely for an affected habitat to recover to unaffected state), T, is equal to 1 / the decay rate. In terms of the Fujioka exponential-form habitat recovery model, then $\rho = 1/T$. To derive this, lifetime to failure (or say, lifetime to recovered habitat, T) is cast as a probabilistic event following an exponential distribution with the exponential “rate” parameter equal to the decay rate, i.e. ρ in the habitat recovery model: $T{\sim}Exp(\rho)$ in standard probability notation. Then the expectation of full recovery time, T, for a given habitat or biological feature is the expectation of an exponential distribution with rate parameter = ρ, and is $1/\rho$. Thus, ρ, the instantaneous rate of recovery, can be interpreted as 1 / the average full recovery time for a given habitat feature.

[f] When determining fishery-specific contributions to basin-wide *LEI* for a given habitat feature – substrate combination by using area-weighted fishing impact rates, as was conducted during the National Marine Fisheries Service 2005 Fujioka-Rose implementation (USDC 2005), all fishing impact units are given

equal weight. For example, consider a single block with three fisheries operating with very high effort and comparable q, ρ (Table FNF.1), leading to fishery-specific contributions as calculated in Table FNF.2.

Table FNF.1 Fishing effect scenarios by three separate fisheries in a single block for a single habitat feature – substrate combination under high fishing impacts.

Fishery	Initial habitat area	f	q	ρ	I	Area weighted I	Equilibrium single-fishery areal loss*
1	10.0	5.0	0.9	0.1	4.3	42.5	9.8
2	10.0	3.0	1.0	0.1	2.9	28.5	9.7
3	10.0	2.0	1.0	0.1	1.9	19.0	8.5
				Totals	9.0	90.0	28.9

* Habitat loss calculated for each fishery in isolation; see equations in Section 2.0 of main text.

Table FNF.2 Fishery-specific contributions to aggregate *LEI* for the single-block scenario in Table FNF.1.

Fishery	Contribution by area weighted I	Contribution by equilibrium single-fishery areal loss
1	47.2%	33.8%
2	31.7%	33.4%
3	21.1%	32.8%

In this scenario, fishery-specific contributions by area-weighted *I* indicate that fishery 1 bears the largest component of the impact on habitat in the block due to fishing, approximately 2.25 times greater culpability than fishery 3. Notice, however, that because each fishery administers high fishing effort on sensitive habitat of slow recovery, each fishery in isolation can produce near complete loss in fishing habitat, as evidenced by the "Equilibrium single-fishery areal loss" column of Table FNF.1. This is reflective of the nonlinear habitat impact dynamics of the Fujioka (2006) model, where equilibrium habitat impact saturates at high impact rates and low habitat recovery (e.g. Figure 1 in Fujioka 2006). Thus, from the perspective of habitat impacts, in this scenario all fisheries share equal culpability in the resulting equilibrium habitat effects as any one in isolation can produce similar habitat effects. To accommodate this, fishery-specific contributions to *LEI* can be apportioned out according to single-fishery habitat impacts (see algorithm below). Results from this weighting scheme are illustrated in column "Contribution by equilibrium single-fishery areal loss" in Table FNF.2, which correctly determines that all fisheries share equal culpability for habitat reduction. Furthermore, apportionment based upon single-fishery habitat loss also behaves similarly to the method of apportionment based upon area-weighted fishing impact rates when fishing impact rates are low and/or recovery rates are high (Table FNF.3 - FNF.4). In this case, fishing impact rates combine nearly linearly because the fishing impact model behaves approximately linearly in this region of habitat impact-recovery dynamics. As indicated by Table FNF.4, both weighting scheme produce nearly identical apportionments of long-term habitat effects to the respective fisheries.

Table FNF.3 Fishing effect scenarios by three separate fisheries in a single block for a single habitat feature – substrate combination under low fishing impacts.

Fishery	Initial habitat area	F	q	ρ	I	Area weighted I	Equilibrium single-fishery areal loss*

1	10.0	0.5	0.2	2.0	0.1	1.0	0.5
2	10.0	0.3	0.2	2.0	0.1	0.6	0.3
3	10.0	0.2	0.2	2.0	0.0	0.4	0.2
				Totals	0.2	2.0	1.0

* see equations in Section 2.0 of main text.

Table FNF.4 Fishery-specific contributions to aggregate *LEI* for the single-block scenario in Table FNF.1.

Fishery	Contribution by area weighted *I*	Contribution by equilibrium single-fishery areal loss
1	50.0%	49.4%
2	30.0%	30.2%
3	20.0%	20.3%

The algorithm to calculate fishery-specific contributions to basin-wide *LEI* for a given habitat feature - substrate combination ($LEI_{\bullet,g,c,s}$; Quantity 3 in Section 3.0 of the main text) using single-fishery habitat loss (as opposed to area-weighted fishing impact rates) is as follows:

Step 5a, calculate fishery-specific impact rates for each block for each habitat feature - substrate combination, $I_{b,g,c,s}$ by multiplying the fishing effort from each fishery applied within a block, $f_{b,g}$, by the appropriate sensitivity parameter specific to a gear - habitat feature - substrate combination, $q_{g,c,s}$:

$$I_{b,g,c,s} = f_{b,g} \times q_{g,c,s} \;.$$

Step 5b, calculate for each block the equilibrium reduction in habitat area under each fishery’s single-fishery impact rate in isolation, $h_{b,g,c,s}$, by calculating single-fishery $LEI_{b,g,c,s}$ and multiplying by habitat amounts in blocks for a pristine, undisturbed system, $A_{b,c,s}$ (i.e. H_0):

$$h_{b,g,c,s} = A_{b,c,s} \times {}^{I_{b,g,c,s}}\Big/_{(I_{b,g,c,s} + \rho_{c,s})} \quad .$$

Step 5c, calculate for each fishery the total single-fishery areal reduction for a given habitat feature – substrate type combination, $h_{\bullet,g,c,s}$:

$$h_{\bullet,g,c,s} = \sum_{b=1}^{B} h_{b,g,c,s} \quad .$$

Step 5d, calculate the basin-wide sum of single-fishery areal habitat reduction across blocks and fisheries for a given habitat feature – substrate combination, $h_{\bullet,\bullet,c,s}$:

$$h_{\bullet,\bullet,c,s} = \sum_{b=1}^{B} h_{\bullet,g,c,s} \quad .$$

Step 5e, finally, determine single-fishery areal reduction contribution weights for each specific fishery by dividing each fishery's aggregate single-fishery areal habitat reduction for a given habitat feature - substrate combination by the total pool of single-fishery areal habitat loss for the habitat feature - substrate combination. These contribution weights are multiplied by the total LEI for the respective habitat feature - substrate combination to give a fishery specific contribution to the equilibrium habitat reduction effect index, $LEI_{\bullet,g,c,s}$:

$$LEI_{\bullet,g,c,s} = {h_{\bullet,g,c,s}}/{h_{\bullet,\bullet,c,s}} \times LEI_{\bullet,\bullet,c,s} \quad .$$

10.0 Acknowledgements

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Appendix 1: R code for Fujioka-Rose long-term effect index analysis: Bering Sea example following analyses presented in the NOAA 2005 Final Environmental Impact Statement for Essential Fish Habitat Identification and Conservation in Alaska (USDC 2005).

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```
# Contents: This R code implements the long-term effect index analysis algorithm
# presented in Section 3.0 of the main text of the FAST lab briefing document.
#  Bering Sea input files were provided by C. Rose, National Marine Fisheries
# Service (Retired), as part of 2005 essential fish habitat assessment for the North
# Pacific Fishery Management Council (USDC 2005).  Input files are available from the
# authors of this briefing upon request.  Variable notation follows that from the main text;
# the core model equations follow those implemented in USDC 2005, which were
# later corrected in Fujioka (2006).  Corrected equations following Fujioka
# (2006) are indicated in code comments, below.

# set working directory
  setwd("Your Directory Here")

# Data input and setup
  F_m <- read.csv("BSEffectsAnalysis.F.csv",header=T)
    # fishing effort matrix, 12242 rows (blocks) x 12 cols (first = block ID, then 11 fisheries)
  q_m <- read.csv("BSEffectsAnalysis.q.csv",header=T)
    # habitat feature sensitivity matrix, 11 rows (fisheries) by 17 cols (1 fishery id,
    # 16 habitat feature - substrate combinations for Bering Sea)
  rho_m <- read.csv("BSEffectsAnalysis.rho.csv",header=T)
    # habitat feature recovery matrix, 1 row by 16 cols (habitat feature - substrate combinations).
  habitat_m <- read.csv("BSEffectsAnalysis.c.csv",header=T)
    # habitat matrix, 12242 (blocks) rows by 17 cols (1 block id, 16 habitat features - substrate
    # combinations). Provides amount of habitat feature - substrate combination area in
    # km2, only for blocks that experienced fishing
  TotalA_m <- read.csv("BSEffectsAnalysis.a.csv",header=T)
    # basin total substrate area, 1 row x 16 cols, combined area of all blocks for each of
    # 16 habitat - substrate type combinations (fished and unfished)

  # set number of habitat features and number of substrates--used for subsequent matrix, vector, and list creation
    num.feature <- 4 # for bering sea: infaunal prey, epifaunal prey,
          # biologically-derived structure, physical structure
    names.feature <- c("InPrey","EpPrey","SubsShelt","BioShelt")
    num.substrate <- 4 # for bering sea: sand, mud/sand, mud, slope
    num.fishery <- 11 # bottom trawl: flathead/other, pacific cod, pollock, rock sole, rockfish, sablefish/turbot
          # yellowfin sole; pelagic trawl: pollock; longline: pacific cod, sablefish/turbot;
          # pot: combined red king crab/tanner crab/snow crab.

  # Remove block label columns where necessary
    F_m <- F_m[,-1]
    habitat_m <- habitat_m[,-1]
    q_m <- q_m[,-1]

# Calculations
  # Calculation Step 1: Calculate total fishing impact for each habitat feature - substrate combination,
  # summing across all fisheries' respective area swept (f) and sensitivity parameters (q).
    I_b.cs_m <- as.matrix(F_m) %*% as.matrix(q_m)

  # Calculation Step 2: Calculate the equilibrium proportion of unaffected habitat, all fisheries combined.
  # Note, in order to replicate results in USDC 2005 by the
  # Fujioka-Rose implementation, the equation for Heqpro_m follows the previously uncorrected
  # version of Fujioka (2006) eq. 4.
    Heqpro_m <- matrix(nr=nrow(habitat_m),nc=num.feature*num.substrate,0) # storage, dimensions of "classification" matrix
```

```
 colnames(Heqpro_m) <- colnames(habitat_m)
 for(i in 1:(num.feature*num.substrate)){
  Heqpro_m[,i] <- rho_m[,i]*exp(-I_b.cs_m[,i]) / ((rho_m[,i]*exp(-I_b.cs_m[,i]))+I_b.cs_m[,i])
  # Corrected equation, provided in Fujioka (2006) and used in the main text:
   # Heqpro_m[,i] <- rho_m[,i]/ (rho_m[,i]+I_b.cs_m[,i])
  } # end i loop over habitat feature - substrate combinations
 # Heqpro_m is dimension 12242 rows (blocks) by 16 cols (habitat feature-substrate combination)

 # Calculate LEI_b.cs, the long term reduction index, specified by block and
 # hab. feat. - sub. combo, combining all fisheries' impact rates combined.
  LEI_b.cs_m <- 1-Heqpro_m

# Calculation Step 3: basin-wide aggregate LEI across all blocks and fisheries
# Calculation Step 3a: block specific areal reductions
 h_bcs_m <- habitat_m * LEI_b.cs_m # this calculates the absolute reduction in habitat in km2, and using
  # the "habitat" matrix as giving block substrate areas for fished blocks only

# Calculation Step 3b[Quantity 1]: Basin wide LEI for each habitat feature - substrate combination,
# all fisheries combined. Calculate for each habitat feature-substrate combination total LEI
# proportionate reduction summed across ALL blocks only, row vector of 16 cols. Thus, this
# is basin-wide equil. prop. reduction in each habitat feature-substrate combo as a result of fishing.
 LEI_..cs_v <- matrix(nr=1,nc=num.feature*num.substrate)
 colnames(LEI_..cs_v) <- colnames(habitat_m)
 LEI_..cs_v  <- colSums(h_bcs_m)/as.numeric(TotalA_m) # Desired Quantity 1 in Sethi and Harris (2014)

# Calculation Step 4 [Quantity 2]: block specific LEI for habitat features, combining fisheries and substrates,
# (i.e. for plotting)
 # First, sum areal reduction in equilibrium for each habitat feature summed across substrate types: 12242 x 4 matrix
  h_bc._m <- matrix(nr=nrow(habitat_m),nc=num.feature)
  colnames(h_bc._m) <- names.feature
  for(j in 1:num.feature){
    h_bc._m[,j] <- rowSums(h_bcs_m[,seq(from=1,to=(num.feature*num.substrate),by=num.substrate)+(j-1)])
    } # end j loop

 # Next, sum habitat feature area across substrate types: 12242 x 4 matrix.
  A_bc._m <- matrix(nr=nrow(habitat_m),nc=num.feature)
  colnames(A_bc._m) <- names.feature
  for(j in 1:num.feature){
   A_bc._m[,j] <- rowSums(habitat_m[,seq(from=1,to=(num.feature*num.substrate),by=num.substrate)+(j-1)])
   } # end j loop
  A_bc._m <- A_bc._m + .00001 # add small amount to avoid dividing by zero

 # Finally, calcluate LEI_b.c._m for each block
  LEI_b.c._m <- h_bc._m / A_bc._m # 12242 x 4 for EBS

# Calcluation Step 5: fishery-specific contributions to basin-wide LEI.  The following code follows the
# area-weighted fishing impact rate allocation scheme implemented in the Rose-Fujioka analysis (USDC 2005).
# See the main text of the FAST briefing document for an alternative allocation scheme based upon
# actual areal reductions associated with specific fisheires.
 # Calculation Step 5a: block- and fishery-specific area weighted fishing impact rates
 IA_bgcs_ls <- list()
 for(j in 1:num.fishery){
  I_bgcs_m <- as.matrix(F_m[,j]) %*% as.matrix(q_m[j,]) # fishery-specific impact factors, 12242 x 16
  IA_bgcs_ls[[j]] <- I_bgcs_m * habitat_m # compute "area weighted" impact factors for fishery
  } # end j loop

 # Calcluation Step 5b: aggregate across blocks for each fishery
 IA_.gcs_m <- matrix(nr=num.fishery,nc=num.feature*num.substrate)
 colnames(IA_.gcs_m) <- colnames(habitat_m)
 for(j in 1:num.fishery){
  IA_.gcs_m[j,] <- colSums(IA_bgcs_ls[[j]]) # a num.feature * num.substrate row vector
```

```
   } # end j loop

  # Calcluation Step 5c: calculate total pool of area-weighted fishing impact rates for each
  # habitat feature - substrate combination
  IA_..cs_v <- colSums(IA_.gcs_m)

  # Calcluation Step 5d: fishery-specific LEI contributions based on area-weighted fishing impact rates
  LEI_.gcs_m <- matrix(nr=num.fishery,nc=num.feature*num.substrate) # create storage and labels cols. and rows.
  colnames(LEI_.gcs_m) <- colnames(habitat_m)
  rownames(LEI_.gcs_m) <- sapply(colnames(F_m),FUN=function(xx){substr(xx,1,nchar(xx)-4)})
  for(j in 1:(num.feature*num.substrate)){
   LEI_.gcs_m[,j] <- LEI_..cs_v[j] * (IA_.gcs_m[,j]/IA_..cs_v[j]) # Desired Quantity 3 in Sethi and Harris (2014)
   } # end j loop

# output quantities of interest
 # basin-wide aggregate long term equilibrium reduction index for each habitat feature - substrate type combination (LEI)
  write.table(LEI_..cs_v,"Quantity1.BasinWideLEI.csv",sep=",",row.names=F)
 # block specific LEI by habitat type (aggregate across fisheries and substrate types)
  write.table(LEI_b.c._m,"Quantity2.BlockSpecificLEI.csv",sep=",",row.names=F)
 # fishery specific contributions to basin-wide LEI for each habitat feature - substrate type combination
  write.table(LEI_.gcs_m,"Quantity3.FisherySpecificLEI.csv",sep=",")

# References:
 # Fujioka, J.T. 2006. A model for evaluating fishing impacts on habitat and comparing fishing closure
 # strategies. Canadian Journal of Fisheries and Aquatic Sciences 63: 2330-2342.

 # Fisheries, Aquatic Science, and Technology Laboratory (FAST;2014). Examination and implementation of the
 # LEI fishing impacts model briefing memorandum.  Pacific States Marine Fisheries Commission
 # project #NA11NMF4370212, Technical Report XXpp.

 # U.S. Department of Commerce (USDC). 2005. Final Environmental Impact Statement for Essential Fish Habitat
 # Identification and Conservation in Alaska. Washington, D.C.: National Marine Fisheries Service Alaska Region
 # Official Document.
```