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A seascape scale habitat model to support management of fishing impacts on
benthic ecosystems

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Abstract

Minimizing fishing impacts on seafloor ecosystems is a growing focus of ocean
management; however, few quantitative tools exist to guide seascape scale habitat
management. To meet these needs, we developed a model to assess benthic ecosystem
impacts from fishing gear contact. The habitat impacts model is cast in discrete-time and
can accommodate overlapping fisheries as well as incorporate gear-specific contact
dynamics. We implemented the model in the North Pacific using fishing data from 2003 –
2017, estimating that habitat in 3.1% of the 1.2 million km² study area was disturbed at the
end of the simulation period. A marked decline in habitat disturbance was evident since
2010 attributable to a single regulatory gear change which lifted trawl gear components off
the seafloor. Running scenarios without these gear modifications showed these policies
may have contributed to a 24% reduction in habitat disturbance since their
implementation. Ultimately, model outputs provide direct estimates of the spatial and

temporal trends of habitat effects from fishing – a key component of regulatory policies for many of the world's fisheries.

1.0 Introduction

Sustainable fisheries management has progressed from a focus on individual stocks to ecosystem based approaches which recognize that habitat integrity is a critical component of healthy fisheries (Pikitch et al. 2004; McLeod and Leslie 2009). A number of options are available to mitigate habitat impacts associated with fishing while minimizing socioeconomic impacts on the fishery, including 1) spatial closures to protect sensitive habitat, 2) policies which reduce effort by increasing capture efficiency, and 3) changes to gear to reduce bottom contact. To support habitat management, analysts require tools to understand the spatiotemporal distribution of fishing effort and associated habitat disturbances in order to weigh the relative benefits and costs associated with different policies to maintain benthic ecosystem integrity. Here we develop a seascape scale habitat impacts model designed with features useful for the fish habitat management process (henceforth, the 'Fishing Effects' model). Building from previous efforts, the Fishing Effects model balances impact and recovery processes using discrete time dynamics which can incorporate seasonality common to most fisheries. Furthermore, the model accommodates habitat disturbance from multiple fisheries and gear types with overlapping fishing effort—a reality common to most marine ecosystems. Developed as spatially explicit and with options to represent gear changes through bottom contact adjustments, the Fishing Effects model is generic enough to support analyses of a wide range of habitat management policies.

Seafloor habitat features create structural complexity, providing protection from predators and forage opportunities for benthic organisms. Structure-forming habitat features vary in function and composition, and include biogenic structures such as coral or shell structures, epi- or infauna, and geological structures such as cobble piles or sand waves. To varying degrees, all benthic habitat features are vulnerable to disturbance associated with bottom-tending fishing activity (Jennings and Kaiser 1998; Thrush et al.

1998; Hall 1999). Biogenic structures, and epifaunal and infaunal organisms may be damaged or completely removed when contacted by fishing gear (Kenchington et al. 2006). Physical features such as cobble and boulder piles may be scattered or dispersed (Freese et al. 1999), and microstructures formed by soft sediment such as sand waves may be resuspended and homogenized (Thrush et al. 1998; Watling and Norse 1998; O'Neill and Ivanović 2016). Mobile fishing gear such as trawls or dredges are often the primary focus of seafloor impact studies, but fixed gears that contact the seafloor also have potential to disturb habitat features, and are often deployed in steep and rocky vulnerable habitats where use of mobile gears is not possible (e.g. Chuenpagdee et al. 2003; Heifetz et al. 2009; Stone et al. 2015; Doherty et al. 2017).

A number of meta-analyses have been conducted to understand the vulnerability of habitats to fishing activities (Collie et al. 2000; Kaiser et al. 2006; Grabowski et al. 2014; Hiddink et al. 2017). However, to support ocean habitat management, tools which scale localized impacts up to the seascape are needed to estimate the cumulative impacts of fishing. A small number of frameworks have been developed for this purpose (Fujioka 2006; Dichmont et al. 2008; NEFMC 2011; Ellis et al. 2014; henceforth referred to as cumulative fishing impacts models). By explicitly combining habitat impacts and recovery to produce an estimate of cumulative fishing effects, these models are differentiated from a number of other seascape habitat models which focus on impacts or habitat vulnerabilities separately (e.g. Hiddink et al. 2007; Halpern et al. 2008; Rijnsdorp et al. 2016). Integrating impacts and recovery into a cohesive framework allows for improved temporal resolution of net habitat effects.

Differences among existing cumulative fishing impacts models can be categorized based upon three structural characteristics: 1) use of continuous versus discrete time, 2) the shape of the habitat recovery curve, and 3) complexity of the model translating fishing effort into habitat impacts. Most adopt a continuous-time dynamic, casting the impact and recovery as a differential equation (Fujioka 2006; Dichmont et al. 2008; Ellis et al. 2014), with only the Swept Area Seabed Impacts model developed by the U.S. New England Fishery Management Council (NEFMC 2011) utilizing a discrete-time dynamic. The benefit of a discrete-time model is that it facilitates habitat disturbance assessments over series of

relevant time steps, whereas continuous-time models are typically used to estimate equilibrium levels of habitat disturbance under assumed constant rates of fishing impact and recovery. Conceptually, recovery is similar among models in that impacted habitats recover naturally over time based upon some prescribed functional shape ranging from logistic (Dichmont et al. 2008; Ellis et al. 2014), asymptotic (Fujioka 2006), or linear (NEFMC 2011).

The existing cumulative fishing impacts models differ more strongly in the way habitat disturbance is modeled as a function of fishing effort. A key process in relating fishing effort to habitat impacts is the treatment of overlapping fishing events in space, where repeated fishing events over already disturbed habitat may have different impacts than fishing events in undisturbed habitats. The Fujioka model (Fujioka 2006) translates summed fishing effort (in units of proportional area swept) to habitat impacts using a 'habitat coefficient' scalar. The models constructed by Dichmont et al. (2008) and Ellis et al. (2014) similarly scale effort to habitat disturbance, but their models also include a process to account for overlapping fishing events, providing flexibility to model habitat disturbance under spatially disparate versus aggregated fishing. With a focus on testing gear modification scenarios, the Swept Area Seabed Impact model (NEFMC 2011) was developed with the most explicit approach to translating fishing effort to habitat impacts by including modules relating gear configuration to bottom contact as well as gear specific habitat susceptibility parameters.

As fisheries management systems mature, many now explicitly include requirements to minimize impacts to fish habitats to the extent practicable (Nimick and Harris 2016). Spurred by needs identified by the U.S. North Pacific Fishery Management Council (NPFMC) for additional model functionality to assess the current state of benthic habitat disturbance at seascape scales and to facilitate analysis of the tradeoffs between different habitat impact reduction options, we developed the Fishing Effects model combining features from a number of existing cumulative fishing impacts models. Specifically, we use a discrete-time framework that incorporates time-varying fishing effort among multiple fisheries. The model is implemented on monthly time scales, reducing problems of estimating impacts using annualized measures of fishing effort (van Denderen

et al. 2015), and includes habitat susceptibility and recovery dynamics that are parameterized to accept information from empirical studies on fishing impacts. Finally, the Fishing Effects model includes a gear contact adjustment parameter useful for evaluating seascape scale effects of fishing gear modifications which reduce bottom contact. Below, we first provide a mathematical description of the Fishing Effect model, defining the habitat state dynamics, and the impact and recovery processes. Subsequently, we describe a workflow to prepare data inputs necessary to implement the model. Finally, we outline three applications of the modeling framework which together exemplify the use of seascape scale habitat impacts models to inform management using the North Pacific as a case study.

2.0 Methods

2.1 Model description

2.1.1 Habitat states

The Fishing Effects model assumes that a region may be comprised of both disturbed habitat, h , and undisturbed habitat, H (see Table 1 for a list of all model parameters). Casting h and H as proportional areas within a region, the total amount of undisturbed or disturbed habitat sums to one: $H + h = 1$. The Fishing Effects model considers transitions between habitat states in discrete time steps, t . Let $\tilde{I}_t$ represent the proportion of undisturbed habitat that transitions to disturbed habitat by fishing impacts from one time step to the next, and $\tilde{\rho}_t$ as the proportion of disturbed habitat that recovers to an undisturbed state over the same time step, leading to the discrete-time habitat state equation:

$$H_{t+1} = H_t(1 - \tilde{I}_t) + h_t\tilde{\rho}_t \tag{1}.$$

Thus far, Eq. 1 implies a single generic model spatial domain. In practice, the model is implemented on a spatially explicit grid indexed by both time, t , and cell, i , such that Eq. 1 governs the dynamics within each grid cell.

A model grid cell can contain multiple habitat types, for example as defined by substrate class (mud, sand, bedrock, etc...), each of which may contain an assemblage of habitat features such as biogenic structures like sponge communities, or physical structures like boulder piles or sand waves. As outlined below, the Fishing Effects model accounts for impacts and recovery by habitat type, representing disturbance to the habitat features associated with each habitat type. Subsequently, for the purposes of calculating the proportion of disturbed habitat within a given cell at a point in time, $H_{i,t}$ is calculated as a weighted mean over habitat types (indexed by s) based on the proportion of each habitat type in the cell, $\phi_{i,s}$:

$$H_{i,t} = \sum_{s=1}^k H_{i,t,s} \phi_{i,s} \quad (2).$$

Although habitat types may be spatially explicit regions within a grid cell, in practice such fine resolution habitat information is usually not available. Thus, it is assumed that each habitat type is distributed uniformly throughout a grid cell, and that the *relative* proportions of habitat types within cells remains fixed across time regardless of whether these habitats are in a disturbed or undisturbed state.

2.1.2 Impacts

The impacts process translates fishing activity into habitat disturbance outcomes. Impacts, I , represent the area of each habitat type in a grid cell that converts to the disturbed state in a time step by a single interaction (e.g. trawl pass, longline set) with fishing gear. Impacts are calculated as the proportionate area of a habitat type in a cell contacted by fishing gear, f , times a habitat susceptibility parameter, q , conceptually similar to the 'catchability' of a habitat feature from fishing gear contact: $I = fq$. To provide

downstream functionality to explore changes to fishing gear, and to track the combined impacts of different fishing gears that overlap during the course of a fishing season, impacts are tracked by fishing events, j (e.g. a single trawl tow, a longline set, etc.), and habitat types, in addition to time and space. Both the amount of seafloor habitat contacted by fishing gear and the susceptibility of habitats to fishing gear contact vary across gear types. We use the notation “(g)” to indicate that a parameter value depends on the fishing gear type. Combining all the indexing variables for subsequent model runs, we have:

$$I_{i,t,s,j(g)} = f_{i,t,s,j(g)} q_{s(g)} \quad (3).$$

The seafloor area contacted by fishing gear will typically be less than the nominal “area swept” because not all gear elements contact the seafloor during fishing (Winger et al. 2010). For example, trawl nets can be rigged with lifting elements to raise towing gear up off the seafloor (Rose et al. 2010; see the Results section below for an example of habitat impact outcomes associated with trawl sweep modifications) Thus, bottom contact, f , is calculated as the product of nominal area swept, A , and gear specific contact adjustment, c :

$$f_{i,t,s,j(g)} = A_{i,t,s,j(g)} c_{j(g)} \quad (4),$$

where A is measured as a proportion relative to the area of a grid cell, and c is a proportion relative to the nominal swept area. In addition to correcting gear bottom contact, the inclusion of a contact adjustment parameter provides functionality to model gear modifications that lift gear elements off the seafloor.

In the course of fishing, a grid cell may experience multiple fishing events with overlapping swept areas, particularly in high effort hotspots on fishing grounds. Thus, fishing impact models need to calculate habitat disturbance under potentially overlapping fishing impacts. To generate combined habitat impacts in the Fishing Effects model, we first sum impacts across m fishing events that occur within a cell in a single time step (the “•” subscripts indicates summation across an index):

$$I_{i,t,s,\bullet} = \sum_{j=1}^m I_{i,t,s,j} \quad (5).$$

186 Subsequently, sum of impacts, I , are translated into proportional impacts which are
 187 constrained between zero and one, $\tilde{I}$, as utilized in Eq. 1:

$$\tilde{I}_{i,t,s} = 1 - e^{-I_{i,t,s,\bullet}} \quad (6).$$

188 While not obvious, the relationship in Eq. 6 implies that fishing events are randomly
 189 distributed within a grid cell (Gerritsen et al. 2013; see Supplemental Material for
 190 derivation of this assumption). If fishing activity is more spatially aggregated than
 191 expected under random fishing, Eq. 6 would produce an overestimation of proportional
 192 impacts (i.e. more overlap than expected). Conversely, uniformly distributed fishing
 193 activity would distribute contact more widely throughout the cell than expected under
 194 random fishing and result in an underestimation of impacts (Ellis et al. 2014). Note, the
 195 scale of the grid cell will affect this assumption. At a seascape scale, fishing activity is
 196 clearly aggregated, but at very small scales (e.g. an area smaller than the swept area of a
 197 single tow) fishing becomes uniformly distributed; the assumption of random fishing effort
 198 is likely to be met at some spatial grain between these two extremes.

199

200 2.1.3 Recovery

201 Most biogenic and physical benthic habitat features exhibit the ability to recover
 202 after disturbance (Grabowski et al. 2014; Hiddink et al. 2017). Habitat recovery, $\tilde{\rho}$, in Eq. 1
 203 is the proportion of disturbed habitat that transitions to undisturbed habitat, from one time
 204 step to the next. The recovery process could take various functional forms, including
 205 density-dependence, or include temporal or spatial dynamics (e.g. Pacific decadal
 206 oscillation regime shifts; Mantua and Hare 2002). Here, we implement a constant habitat
 207 recovery rate function whereby recovery dynamics follow an exponential asymptotic

trajectory parameterized by a mean time to recovery, $\bar{\tau}$, specific to different habitat types (indexed by s):

$$\tilde{\rho}_{i,t,s} = 1 - e^{(-1/\bar{\tau}_s)} \tag{7}.$$

Conceptually, this model reflects the cumulative probability that an impacted habitat will transition to an undisturbed state as a function of a mean time to recovery (Fig. 1). To facilitate interpretation of recovery times, we present recovery parameters both in terms of the mean recovery time, and the time at which cumulative probability of recovery is 95%, τ^* , where $\tau^* = -\bar{\tau} \ln(1 - 0.95)$.

2.2 Model implementation

Requirements to implement the Fishing Effects model include: 1) a defined spatial domain with an appropriately-sized grid overlay, 2) the spatial distribution of habitat types 3) fishing event locations, most likely derived from electronic monitoring such as vessel monitoring system (VMS) data, 4) nominal gear width and gear contact adjustments for each fishing event, and 5) habitat susceptibility and recovery parameters. Here, we describe each of these inputs using an implementation of the model in the North Pacific as an example.

2.2.1 Spatial domain and habitat distribution

The case study area is the North Pacific continental shelf within the United States Exclusive Economic Zone at depths less than 1,000 m, resulting in a model domain of 1.2 million km². We split the domain into three subregions that align with management units of the NPFMC: Aleutian Islands, Bering Sea, and Gulf of Alaska. All three subregions contain multiple fisheries and gears with different bottom contact intensities (e.g. bottom trawl vs. longline). The Aleutian Islands are characterized by steep, rocky and overall more variable terrain than the other subregions. The Bering Sea is characterized by a large and

flat continental shelf of homogenous soft habitat, extending over 500 km off the coast. The Gulf of Alaska also sits on a large continental shelf but is incised by deep troughs and contains many rocky outcrops.

We implemented a 5 km x 5 km model grid, reflecting the spatial resolution of available fishing and habitat information within the North Pacific (NOAA 2017b). Detailed information on the spatial distribution of specific benthic habitat features was generally lacking; however, observations from sediment surveys in the North Pacific were more widely available. Thus, we used sediment-based habitat types (mud, sand, granule/pebble, cobble, and boulder) and developed a GIS workflow to map the sediment observations across the domain. Sediment observations (232,517 total points) were compiled from disparate surveys (Smith and McConnaughey 1999; NOS 2013, Zimmermann et al. 2013; Zimmermann and Prescott 2015) in a GIS, and parsed using a text mining algorithm (Feinerer and Hornik 2017) to map 8,861 different sediment labels onto the five primary sediment types. Subsequently, indicator kriging interpolation (Geospatial Analyst, ArcGIS v10.4.1) was used to create a presence/absence surface for each sediment on a 2.5 km grid, with the presence of each sediment type indicated by a 1 (present) or 0 (absent). This resulted in four sediment subcells nested within each 5 km model grid cell. Subsequently, we calculated the proportions of the sediment type within a 5km grid cell, $\phi_{i,s}$, by standardizing the sum of presences for a particular sediment type among subcells against the sum of presences for all sediment types in the cell:

$$\phi_{i,s} = \frac{\sum_{k=1}^4 \pi_{i,s,k}}{\sum_{k=1}^4 \sum_{s=1}^5 \pi_{i,s,k}} \quad (8),$$

where π is an indicator variable equal to 1 if a sediment type is present, or 0 if not, for subcell k .

2.2.2 Fishing gear and fishing effort

Spatially explicit fishing effort was obtained from the US National Marine Fisheries Service, consisting of VMS tracks of federally managed commercial vessels.

Implementation of VMS has been ongoing since 2003 in the North Pacific, with full coverage of nearly all vessels using bottom-tendered fishing gear. Omission from this dataset are primarily small longline and pot vessels which would have no discernable impact on regional model outputs. Gear specific nominal widths and contact adjustment parameters were taken from a database of gear dimensions compiled by the NPFMC (2017; see Table S6, Supplemental Material). Unique nominal gear widths ranged from 50.0 m – 259.0 m for 59 variants of trawls, 2.0 m for longlines, and 5.6 m for pot sets. For longlines and pots, the nominal widths were calculated based on the area potentially impacted from setting or retrieval of the gear, up to three times the footprint of the gear itself. The polylines of fishing activity were buffered by one-half the nominal widths and intersected with the 5 km grid (ArcGIS v10.4.1). Contact adjustment was reported in the database as an estimated range (minimum – maximum) for each gear type. We ran the model using the mean of these values for each gear type (see Fig. S3, Supplemental Material for sensitivity of model outputs to these ranges). To reflect the implementation of required raised sweep gear modifications on flatfish targeting vessels in 2011 for the Bering Sea fisheries (50 C.F.R. § 679, 2010) and in 2014 for Gulf of Alaska fisheries (50 C.F.R. § 679, 2014), contact adjustment parameters were set to unity (complete contact) prior to their implementation, and ranged from 0.20 to 0.75 afterwards (i.e. 25% - 80% reduction in seafloor contact; NPFMC 2017). The gear modifications generally consisted of 25 cm disks placed on the trawl sweeps. Experimental studies showed slight reductions on catch rates of some flatfish species with these modifications (Rose et al. 2010b), but caused significantly less damage to sessile invertebrate compared to conventional gears (Rose et al. 2010a). To test for random effort within a grid cell, we used a subset of the VMS data to evaluate this assumption, finding that while most grid cells the North Pacific do demonstrate relatively random effort, about 10% of the grid cell had substantially aggregated fishing effort. This may result in a small overestimate (~0.13 percentage points) in habitat disturbance from model outputs (Fig. S1, Supplemental Material).

2.2.3 Susceptibility and recovery

Habitat susceptibility and recovery parameters characterize benthic ecosystem vulnerability to fishing impacts, translating fishing events into habitat disturbance reflecting a balance of impact and recovery processes. Habitat disturbance may be measured in a variety of ways (e.g. damaged individuals, loss of biomass, decrease in species richness, etc.), thus the parameterization of recovery and susceptibility will define how to interpret disturbance. For this implementation, we adapted susceptibility and recovery values from the Grabowski et al. (2014) review of habitat feature vulnerabilities to fishing gear, which framed recovery and susceptibility as habitat functionality to provide shelter for fish species. We used the Grabowski et al. (2014) study specifically because they accounted for contact adjustment in their estimation of susceptibility. These values were reported as ranges for structural seabed features associated with each habitat type (see Tables S1-S5, Supplemental Material). In running the baseline model, we calculated a mean susceptibility value among seabed features for each habitat-gear interaction and a mean recovery for each habitat type. Mean susceptibility was similar across all sediment types for trawl gears ($q \approx 0.30$) and among fixed gears (longlines and pots, $q \approx 0.14$). Mean recovery ranged from $\bar{\tau} \approx 2.2$ years ($\tau_{95} \approx 6.7$ years) for mud to $\bar{\tau} \approx 3.1$ years ($\tau_{95} \approx 9.2$ years) for boulder habitats (Table 2).

2.2.4 Initial conditions

Options for initial habitat conditions for a model run, H_0 , include starting from “pristine” undisturbed habitat, a case-specific set of initial conditions that match known habitat states, or equilibrium initial conditions based upon a “burn in” period under simulated fishing effort. With insufficient data available to determine the spatial distribution of impacts prior to 2003, but operating on the assumption that impacts were present, we used a “burn in” approach for the North Pacific. To calculate H_0 , we first randomly selected a value for an initial H_0 from a uniform distribution (0.0 to 1.0) for all grid cells that had nonzero fishing effort from 2003 – 2017. We then ran the model using a 30 year burn-in simulated using the first three years of fishing data (2003 – 2005) repeated ten times, which provided ample time for the model to lose dependence on the initial H_0

and reach a stable habitat state. The terminal month of the burn-in period was then used as H_0 for the full 2003 - 2017 model run. Sensitivity analyses showed that choice of initial conditions were likely to have little influence on estimates of habitat disturbance by end of the model run (Fig. S3, Supplemental Material).

2.3 Model applications: management scenarios

Ultimately, the goal of a Fishing Effects model implementation is to inform management of benthic habitat disturbances associated with commercial fishing. Key information needs for habitat management are the spatial and temporal trends in habitat disturbance, and evaluation of past or future policies. To demonstrate the utility of the Fishing Effects model for informing habitat management decisions, we considered two use cases. First, we assessed the historical trajectory and current state of habitat disturbance across the North Pacific. Model outputs were aggregated over the total domain and subregions by summing disturbed area across grid cells and reported as a proportional to the respective region of analysis (equivalent to averaging proportional disturbance across grid cell). Second, we used the model as a retrospective tool to evaluate outcomes associated with past policy actions. For this case, we estimated the net reduction in habitat disturbance associated with the implementation of sweep modifications for demersal trawl fisheries implemented in 2011 for the Bering Sea fisheries and 2014 for Gulf of Alaska fisheries. We compared model runs with and without (i.e. $c = 1$ for 2011 and beyond) the sweep modifications to isolate the efficacy of the policy to reduce habitat disturbance. Policy effects were quantified as the percent reduction in total disturbed habitat under sweep modifications relative to the case of no sweep modifications.

3.0 Results

3.1 Model inputs for the North Pacific

The combined North Pacific (<1,000 m depth) model domain is predominately sand (52%) and mud (32%), with lesser amount of cobble (10%), granule/pebble (6%), and boulder habitat (<1%; Table 3; see Fig. S2, Supplemental Material for sediment distribution

maps). The Bering Sea and Gulf of Alaska subregions had similar habitat proportions, with slightly less rocky substrate (granule/pebble and cobble) in the Bering Sea (8%) than the Gulf of Alaska (23%). The Aleutian Islands had a substantially different sediment profile, with more cobble (36%) and less mud (1%) than the other two sub regions.

Fishing effort was not uniformly distributed among sediment types. Proportionally, fishing occurred more on sand than other sediment types, accounting for 64% of the nominal fishing effort -- about 25% greater than the proportion of sand in the North Pacific at large. Mud sediment (31% of nominal effort) were fished relatively equal to its proportional coverage in the North Pacific. Gravel/pebble sediments (4% of nominal fishing effort) were fished about 30% less. Cobble (2% of nominal fishing effort) and boulder (<1% of nominal fishing effort) were both fished about 80% less than their respective coverages.

Total yearly nominal swept area across all gears summing overlapping effort ranged between 106,000 km² (2010; 7.1% of the total area) and 146,000 km² (2016; 11.6% of the total area) with a mean 9.8% over the 2003-2017 study period (Fig. 2). Domain-wide, demersal otter trawls were the most common type of gear used, followed by longlines and pots. Fishing effort was proportionally greatest in the Bering Sea (mean annual nominal area swept 2003 to 2017 = 13.7%) compared to the Aleutian Islands (mean = 4.2%) and the Gulf of Alaska (mean = 2.5%).

3.2 Model application: management scenarios

Using realized fishing data from 2003-2017, the Fishing Effects model estimates that 3.1% of habitat in the North Pacific model domain was in disturbed state at the end of the assessment period (December 2017). Habitat disturbance in the Bering Sea (4.1%) was over twice that estimated for the Aleutian Islands (1.7%) or Gulf of Alaska (1.3%; Fig. 3). Domain-wide, overall habitat disturbance decreased after 2009 (Fig. 3), presumably as a result of reduced fishing effort in 2009 and 2010 (Fig. 2), and implementation of gear regulations requiring trawl sweep modifications in 2011 and 2014. This decline was most

apparent the Bering Sea, while habitat disturbance in the Aleutian Islands and Gulf of Alaska remained relatively stable through all modeled years (Fig. 3). The Fishing Effects model captured seasonal fluctuations in habitat disturbance of up to ± 0.25 percentage points (Fig. 3), reflecting the strong seasonality in fishing effort in the North Pacific. Habitat disturbance tended to reach the highest levels in the Fall (Aug – Oct), and lowest in winter months (Dec – Feb).

Habitat disturbance was highly spatially aggregated throughout the North Pacific (Fig. 4). About 38% of grid cells experienced zero fishing activity (i.e., 0% habitat disturbance) since the start of the study period, and relatively high disturbance cells ($>25\%$) were rare, making up approximately 3% of the domain (Fig. 5). Among subregions, the Bering Sea had a higher proportion of cells (44%) that were unfished compared to the Aleutian Islands (29% unfished) or Gulf of Alaska (34% unfished). However, the Bering Sea also had substantially higher proportion (10%) of moderate to heavily disturbed grid cells (defined here as $>10\%$ disturbance) compared to the Aleutian Islands (4%) or Gulf of Alaska (3%). In contrast, the Aleutian Islands and Gulf of Alaska had substantially higher proportion of grid cells (58% and 53%, respectively) with small, but nonzero disturbance ($>0\% - 1\%$ disturbance), compared to the Bering Sea (23%). This reflects the higher prevalence of longlines and pot fishing gears utilizing habitat in these subregions that is inaccessible to trawls (e.g. steep and rocky terrain) but which themselves have a relatively small contact footprint.

Using the Fishing Effects model as a retrospective policy evaluation tool, we found that in the North Pacific at large, the current estimate of habitat disturbance is about 24% lower than if the trawl sweep gear modifications had never been implemented (Fig. 3). This effect was most pronounced in the Bering Sea (25% reduction in disturbance), which had a higher proportion of gear modified trawl fisheries, as compared to the Gulf of Alaska (21% reduction). The Aleutian Islands, which had no required gear modifications, had no corresponding reduction in habitat disturbance.

4.0 Discussion

The Fishing Effects model provides fisheries managers a quantitative tool to assess seascape scale impacts to benthic habitats from fishing. The primary outputs are spatiotemporal estimates of habitat impacts, providing information about the current state of habitat, and revealing trends that may not easily be identified through conventional scientific survey efforts alone, especially at seascape scales. Casting the model in discrete time is a marked departure from models of similar scope (Perry et al. 2005; Fujioka 2006; Dichmont et al. 2008), providing a framework for inclusion of time-varying impacts and recovery. Model output clearly demonstrates that habitat impacts vary both at seasonal and yearly scales, owing to the timing of fishery openings, fleet behavior, and adaptive management decisions. Though not implemented here, time varying recovery dynamics that reflect seasonal or long term climate cycles such as El Niño/La Niña (Thrush and Whitlatch 2001), or persistent climate warming (Perry et al. 2005; Harley et al. 2006) could also be implemented if information on these relationships were available. An additional advantage of a discrete time model is that it enables analysts to project the habitat effects from management decisions in finite time horizons that align with the fishery management process.

We estimated current habitat disturbance to be 3.1% of the modelled North Pacific domain, with higher predicted disturbance in the Bering Sea compared to the Aleutian Islands or Gulf of Alaska. While proportionally a small area – mainly due to a combination of an ecosystem fishery harvest cap (2 million mt), large spatial closures, unfishable areas, and regions too far from ports to be economically viable – 3.1% represents over 37,000 km² of disturbed habitat. Differences among the subregions generally followed the relative effort in each area, with the highest intensity of fishing effort in the Bering Sea. Aggregate habitat disturbance in the North Pacific demonstrated a declining trend, especially in the Bering Sea, beginning with decreased effort in 2009 and 2010 from reductions in walleye pollock (*Gadus chalcogrammus*) quotas (NOAA 2017b) and continued beyond 2010 from implementation of gear modifications in 2011 and 2014. Because of the time scales required for recovery, habitat disturbance continued to decline beyond 2014, even though the cumulative amount of impacted habitat remained relatively constant.

As a means to evaluate the efficacy of past policies, we used the Fishing Effects model to assess the positive effect gear modifications may have on habitat disturbance. By comparing scenarios with and without gear modifications, we demonstrated trawl gear modifications are associated with an estimated 24% habitat impact reduction by the end of the model run time period (December 2017). We note that the difference in the proportions of estimated domain-wide disturbance is small between the baseline and no gear modification scenarios; however, this reflects the large spatial scale of the model domain relative to the scale of individual fisheries and includes regions closed to fishing.

Mapping habitat impacts at seascape scales carries a high information burden, owing to the complexity of marine ecosystems and variable fishing practices. Of the data inputs used in this implementation, the spatial distribution of habitats is the least resolved – a common limitation throughout seascapes globally (Kaiser et al. 2016). While large swaths of the North Pacific study domain are characterized by relatively homogenous soft bottom habitats, other benthic ecosystems have much greater habitat diversity and incorporation of higher resolution habitat data could improve the specificity of model applications (e.g. Williams et al., 2011; Eno et al., 2013). While habitat information was difficult to find, model applications presented here benefitted from a nearly complete VMS database providing a high-quality data source for fishing effort. Implementing the model in other regions may prove challenging if VMS coverage is not as extensive, or if the VMS data is confidential and not available to analysts (Hinz et al. 2013). Given that fishing effort and habitat information are the key inputs into habitat impacts models, investments into these data sources will be critical for monitoring and managing habitat impacts associated with fishing.

We further capitalized on a gear database developed for the North Pacific with industry and management partners (NOAA 2017a). The specificity of nominal gear widths and contact adjustments enabled a high degree of confidence when scaling VMS tracks to swept areas. Still, gear configurations may vary by fishing behavior or ocean conditions from one tow to the next (Somerton and Weinberg 2001). Improvements in the resolution of these gear parameters may be achieved with further collaboration with industry partners to collect tow-level data streams of gear mensuration often already utilized by

vessel captains. For fixed gears (e.g. pot sets or longlines), their total swept area footprint is expected to be less than that for mobile gears, they may be deployed in steeper and rockier habitats that tend to be more vulnerable to impacts. Thus, better understanding of their footprint and associated impacts is warranted.

While site-specific empirical studies to evaluate benthic ecosystem habitat impacts from fishing are critical for understanding marine ecosystem ecology, scaling up impact and recovery processes to the basin-wide scales needed to monitor and manage fishing impacts has remained a challenge. The Fishing Effects model provides a framework to map the distribution and nature of fishing effort into habitat outcomes at seascape scales. By incorporating discrete time dynamics and functionality to relate gear designs to habitat impact outcomes, the Fishing Effects model can be used to evaluate the effectiveness of habitat management strategies, and to test hypotheses about the impact and recovery dynamics of benthic ecosystems under fishing stress.

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Figure captions

Figure 1. Examples of discrete monthly recovery trajectories. The points show percentage of undisturbed habitat in monthly time steps under $\bar{\tau} = 1, 3$, and 5 year recovery scenarios, corresponding to $\tau_{95} = 3, 9$, and 15 years, respectively. Undisturbed habitat is initially set at 0% ($H_0 = 0; h_0 = 1$) with no subsequent impacts.

Figure 2. Timeseries of yearly nominal swept area for Aleutian Islands (AI, red lines), Bering Sea (BS, blue lines), Gulf of Alaska (GOA, green lines) subregions, and North Pacific at-large (black lines). The vertical axis is the sum of all swept area over a year from nominal gear widths (not contact adjusted) and sums across overlapping efforts. Nominal swept area is represented as a percent of the indicated spatial domain.

Figure 3. Predicted habitat disturbance for Aleutian Islands (AI), Bering Sea (BS), Gulf of Alaska (GOA) subregions, and the North Pacific at-large on monthly time steps from all commercial fishing activities for 2003 – 2017. The solid lines show the baseline models for each region. The dashed lines show scenarios with no gear modifications.

Figure 4. Habitat disturbance estimates on a 5 km grid at the terminal month of the model run (December 2017). The spatial domain of the output is clipped to depths less than 1,000 m, outlined by the thin grey line. The solid black lines indicate US Exclusive Economic Zone and subregion boundaries. Warmer colors indicate higher disturbance, cooler colors indicate lower disturbance. White indicates regions with no fishing activity.

Figure 5. Frequency distributions of habitat disturbance among grid cells in December 2017 for Aleutian Islands, Bering Sea, Gulf of Alaska subregions and the North Pacific at large.

Tables

Table 1. Model parameters and indices.

Model Parameters	Description
H	Undisturbed habitat
h	Disturbed habitat
l	Proportional impacts
$\tilde{\rho}$	Proportional recovery
$I_{i,t,s,j(g)}$	Impact from a fishing event
$f_{i,t,s,j(g)}$	Ground contact by a fishing event
$q_{s(g)}$	Susceptibility
$A_{i,t,s,j(g)}$	Nominal swept area by a fishing event
$c_{j(g)}$	Contact adjustment
$\bar{\tau}_s$	Mean time to recover
$\phi_{i,s}$	Proportion of habitat type s in cell i
Indexing variables	
i	Grid cell, for n total cells
t	Time step
s	Habitat types, for k total habitats
j	Fishing event, for m total events
g	Gear type, for r total gears

19 Table 2. Susceptibility and recovery parameter means from aggregation of habitat features associated with each habitat type.

Habitat type	Susceptibility			Recovery	
	Trawls	Longlines	Traps	Mean recovery ($\bar{\tau}$)	95% recovery (τ_{95})
Mud	0.30	0.13	0.16	2.2 years	6.7 years
Sand	0.32	0.12	0.13	2.4 years	7.3 years
Granule/pebble	0.28	0.13	0.14	2.9 years	8.7 years
Cobble	0.32	0.13	0.15	2.9 years	8.8 years
Boulder	0.30	0.14	0.15	3.1 years	9.2 years

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21 Table 3. North Pacific and subregion areas, fishing effort, and sediment profiles.

	Area (1,000 km ²)	Mean yearly fishing effort	Sediment profile				
			Mud	Sand	Granule/ pebble	Cobble	Boulder
North Pacific at-large	1,248	9.8%	32%	52%	6%	10%	<1%
Aleutian Islands	108	4.1%	1%	46%	17%	36%	<1%
Bering Sea	801	13.7%	35%	57%	3%	5%	0%
Gulf of Alaska	339	2.5%	33%	44%	11%	12%	<1%

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23 ¹Mean yearly nominal swept area 2003 – 2017 as percentage of total area, not accounting for

24 overlapping effort

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Figure 1. Examples of discrete monthly recovery trajectories. The points show percentage of undisturbed habitat in monthly time steps under $\tau = 1, 3$, and 5 year recovery scenarios, corresponding to $\tau_{95} = 3, 9$, and 15 years, respectively. Undisturbed habitat is initially set at 0% ($H_0=0;h_0=1$) with no subsequent impacts.

84x56mm (300 x 300 DPI)

Figure 2. Timeseries of yearly nominal swept area for Aleutian Islands (AI, red lines), Bering Sea (BS, blue lines), Gulf of Alaska (GOA, green lines) subregions, and North Pacific at-large (black lines). The vertical axis is the sum of all swept area over a year from nominal gear widths (not contact adjusted) and sums across overlapping efforts. Nominal swept area is represented as a percent of the indicated spatial domain.

84x56mm (300 x 300 DPI)

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169x127mm (300 x 300 DPI)

Figure 4. Habitat disturbance estimates on a 5 km grid at the terminal month of the model run (December 2017). The spatial domain of the output is clipped to depths less than 1,000 m, outlined by the thin grey line. The solid black lines indicate US Exclusive Economic Zone and subregion boundaries. Warmer colors indicate higher disturbance, cooler colors indicate lower disturbance. White indicates regions with no fishing activity.

170x70mm (300 x 300 DPI)

Figure 5. Frequency distributions of habitat disturbance among grid cells in December 2017 for Aleutian Islands, Bering Sea, Gulf of Alaska subregions and the North Pacific at large.

84x84mm (300 x 300 DPI)