# Question 1

Pacific cod (*Gadus macrocephalus*) are a wide-ranging species that occur from the ranges of Japan to California. Currently, my prevailing hypothesis for Pacific cod stock structure in Alaska separates Pacific cod into 4 stocks, which include the Bering Sea (BS) (combined northern and eastern), the Aleutian Islands (AI), the western Gulf of Alaska (WGOA), and the eastern GOA (EGOA). The stock structure for Pacific cod is likely a result of the combination of environmental (i.e., oceanographic breaks between EGOA and WGOA, as well as Unimak and Samalga Pass) and life-history processes (i.e., natal homing dynamics and semi-adhesive eggs), which I will further discuss below.

Within the BS region, recent changes in the locations in which Pacific cod are caught have resulted in some speculation of sub-stock structure in the BS. However, studies have shown that ***individuals residing in the BS are a single stock***, and there lacks stock structure between the EBS and NBS. Their recent occurrence in these regions are likely due to changes in distribution in response to climate warming, rather than a genetically distinct stock between the EBS and NBS (Spies et al. 2020). This is evidenced by the fact that individuals caught in the NBS had loci (via RADSeq) that clustered from various locations in the EBS (n = 3 locations in the EBS). Further, this is also evidenced by the fact individuals sampled in the NBS had higher genetic diversity than those individually considered in the EBS. If the NBS represented a separate population, established via founder effects, you would expect reduced genetic variability. Thus, their recent expansion into the NBS is likely due to a feeding migration as a result of climate impacts, and individuals residing within the BS most likely constitute a single stock.

Although previous management boundaries have defined the BS and AI as a single stock, recent work has confirmed that these two regions constitute separate stocks (Spies 2012; Drinan et al. 2018). ***The stock structure between the BS and AI*** likely results from a transitional zone located at Samalga Pass, where there are differences in productivity, as well as species composition. Pacific cod may be locally adapted to these differences for both spawning and feeding purposes. Furthermore, the complexity of oceanographic circulation and dynamics in the Aleutian Islands (volcanic islands with substantial water exchange) coupled with natal homing dynamics from Pacific cod likely limit both larval and adult dispersal (Spies 2012). In particular, the presence of deep trenches and passes along the Aleutian Islands may limit the dispersal of adults, given their preference for depths of about 260m. Strong tidal currents are present in these regions, coupled with semi-adhesive eggs, can act to entrain and retain both larvae and eggs within the AI region. This stock structure is supported by studies that have used RADSeq for population assignments, where they were able to assign individuals from the BS and AI back to their population of origin with about 80% accuracy (Drinan et al. 2018). Additionally, the presence of stock structure between the BS and AI are also speculated to be arise from sea-ice dynamics in the Bering Sea, which could be acting selectivity on the genome of Pacific cod, and may further drive local adaption and stock structure in these stocks. In particular, the Bering Sea is characterized by the cold pool and sea-ice dynamics, both of which are absent in the Aleutian Islands; these selective forces have been hypothesized to be act upon the ZP3 gene which regulates glycoproteins and antifreeze proteins for the embryo (Spies et al. 2021). Furthermore, the use of Pool-Seq (I think PoolSeq is better than RADSeq, although I’m not a geneticist..) detected several islands of differentiation between the BS and AI stocks, associated with vision-related genes (Spies et al. 2022). Differentiation was found to be correlated/related to differences in salinity, velocity, chlorophyll, followed by temperature. It is likely that differentiation due to vision-related genes could be due to differences in light penetration, which is lower in the EBS than in the AI, and suggests that these vision-related genes combined with the ZP3 gene may act to select for certain individuals, resulting in stock structure between these regions (i.e., darker in EBS because of sea-ice, and the need to be locally adapted).

***Within the GOA, two separate stocks likely exist between the WGOA and EGOA***, potentially driven by oceanographic breaks as well as natal homing dynamics. Genetic population assignment studies have found that differences between stocks located off of Kodiak and Shumigan Island (i.e., WGOA) with Prince William Sound (PWS) (i.e., EGOA) (Drinan et al. 2018), which is further supported by recent genetic studies (i.e., see Fig 2.1 and 2.2 of Barbeaux et al. 2023). In addition to the recent population assignment studies that have utilizes outlier loci for assignment purposes, studies looking at the ZP3 loci (related to the production of antifreeze proteins and proteins to protect the embryo) have similarly found genetic differentiation between the EGOA and WGOA, suggesting stock structure and differences in haplotype frequencies for this loci that may perhaps explain stock structure between the EGOA, WGOA, EBS and AI (Spies et al. 2020, 2021). Thus, similar to differentiation between the EBS and AI, there are likely selective processes acting upon these populations. In particular, these selective processes may be due to the narrower thermal tolerance of eggs for individuals located west of Kodiak Island (i.e., the WGOA, BS , and AI; Spies et al. 2021). Stock structure between the WGOA and EGOA are also likely due to differences in oceanographic dynamics between these regions. Specifically, IBM larval connectivity studies have shown that the PWS (fish from upstream of PWS to southeast AK) and Kodiak/Shumigan Island regions most likely serve as collection regions for Pacific eggs and larvae. Collection regions forming in the PWS area are likely due to a narrow continental shelf around the EGOA, and impingement of the Alaska current as well as periodic eddies that occur in that region (i.e., Yakutat, Sitka, Haida eddies) (Hinckley et al. 2019), coupled with a transition in this region from the wide and slow moving Alaska Current into the narrow and fast Alaska Stream.

Although there is stock structure between these 4 regions, most likely a result of both environmental and life-history dynamics, there also exists mixing between these stocks. With respect to movement dynamics, both conventional tagging and electronic tag studies have shown that Pacific cod undertake seasonal feeding (spring and summer) and spawning migrations (fall and winter) and can exhibit high movement rates, traversing long distances (Shimada and Kimura 1994; Bryan et al. 2021). Shimada and Kimura 1994 found that Pacific cod tagged in the EBS appear to be able to move into the WGOA (near Shumigan Islands) and some preliminary tagging studies have confirmed this as well (introduction and Figure 2.2 in Hulson 2023) Similarly, fish tagged in the AI have been recaptured in the BS, suggesting some degree of connectivity between the EBS, WGOA, and AI regions (Shimada and Kimura 1994; Bryan et al. 2021). Despite some studies suggesting that deep trenches and passes within the AI may inhibit Pacific movements into the EBS (Spies 2012), limited pop-up satellite tagging studies have found that some Pacific cod individuals can swim across these deep passes in the AI. However, this may be the exception rather than the rule, given the limited number of tags these conclusions were inferred from (Bryan et al. 2021). Nonetheless, it does suggest that Pacific cod are capable of moving through deep passes. Lastly, there are few studies evaluating movement dynamics within the GOA. However, some preliminary tagging studies suggest that there is some degree of connectivity between the EGOA, WGOA, and CGOA (introduction and Figure 2.2 in Hulson 2023).

# Question 2

As discussed above, the most likely biological structure of Pacific cod involves 4 populations, which includes the BS, AI, WGOA, and EGOA, where there is likely seasonal movements and mixing into these regions, particularly during the spring and summer months. ***However, the current management structure assesses all of these components as separate stocks (aside from the GOA), as opposed to having metapopulation structure, and assumes that no immigration or emigration occurs within these regions. Furthermore, the WGOA and EGOA stocks are assessed and managed as a single stock, despite there being evidence of stock structure between these areas.*** The misalignment between management and biological structure is likely a combination of a variety of factors, which can include: 1) management structure being influenced by politics, which were matched up with the biological structure for ease of management, 2) practices for how data should be sampled (i.e., how observer sampling is conducted, although I’m not expert on this…), which likely coincide with defined management structure, 3) based on historical ecological theory that led to management structures remaining static, because of a lack of evidence/not enough studies to suggest that they should be realigned (also because only recently has genomics and tagging methods substantially improved), and 4) insufficient data and resources to support the management of a metapopulation/a stock exhibiting fine-scale population structure.

Several consequences of misaligning management and biological structure can be envisioned. Firstly, within the context of an assessment, “demographic leakage” could occur, where the incorrect processes are averaged across each other (e.g., growth, mortality, productivity), which has the potential to result in incorrect estimates of stock status and abundance (Berger et al. 2021). Furthermore, movements outside of the assessed areas (i.e., not accounting for biological structure correctly) can lead to the misperception that one of the stocks are depleted, while another stock is experiencing an influx of fish, when in reality, abundance of these two stocks combined has not changed. In an example of unidirectional movement outside assessed areas, Berger et al. 2021 demonstrated that significant biases can arise in estimates of population status and resultant management advice, such that there was potential for certain stocks being over or under-utilized, which may enhance the probability of localized depletion for certain stocks. In the classic example of Atlantic cod, a misalignment between the biological and management boundary played a central role in driving its collapse. Specifically, a misleading index of abundance from the inshore fishery led to the perception of a healthy stock status, despite offshore populations being more declined, and a shift in fish distribution towards southern regions. The misalignment and aggregated assessment of offshore and inshore regions led to the misperception of healthy stock status and overestimates of productivity, resulting in increased harvest even when the stock was declining and shifting its distribution (Cadrin 2020). Furthermore, although some studies have demonstrated that system-wide values derived from incorrect assumptions regarding biological structure can be unbiased, similar to themes discussed above, resultant management reference points can be biased, particularly when there is complex fine-scale population structure and movement dynamics (e.g., natal homing dynamics as in Pacific cod) (Goethel and Berger 2017).

Current approaches for managing Pacific stock include three separate stock assessments, coupled with catch allocation methods within the GOA and AI. In particular, catch apportionment is based upon the relative survey biomass in the WGOA and EGOA and the system wide reference point is allocated based on those proportions. The AI regions is also apportioned similarly, although across three areas: the eastern, central, and western AI (Hulson 2023; Spies et al. 2023). There does not appear to be area-specific catch allocations within the EBS (Barbeaux et al. 2023). Importantly, note that survey biomasses are indexed during the summer, where it is known that Pacific cod undertake feeding migrations, and mix with other stock components of Pacific cod in Alaska during this period. While current catch-allocation approaches attempt to distribute fishing effort based upon the relative biomass in specific regions, it is not generally well understood how appropriate this approach is to protecting stock-specific biomass. Simulation studies have suggested that the performance of utilizing relative biomass to allocate catches will likely depend on movement dynamics as well as the error in the given index (Bosley et al. 2019). In particular, catch-allocation schemes such as the one described above generally perform well for stocks that exhibit limited movement, but perform similarly when compared to when catch is allocated equally across areas. Furthermore, when movement and mixing is present across areas, the range of values that optimizes yield (in this case, I am considering maximum system-wide yield) is broader, given that exchange of individuals between regions allow for a broader set of area-specific strategies (non-independence from stocks). ***Considering the potential for cross boundary interactions, complex movements dynamics of Pacific cod, and the timing of survey indices typically utilized for catch-allocation purposes, I hypothesize that the current spatial management delineations and strategies for managing Pacific cod is suboptimal***. In particular, it is likely that survey indices collected in the summer reflect a mixture of individuals from any of the 4 regions defined above. Furthermore, given the complex mixing and movement dynamics of Pacific cod, single-area assessments for these different stock components likely inhibit the potential to explore different area-specific harvest strategies (i.e., the idea of a broader yield isopleth in Bosley et al. 2019) that produce similar levels of yield, while reducing the probability of localized depletion. Together, the combination of misaligning stock structure and ignoring cross-boundary movements (I really only focused on AK here for time, but these ideas can be extended if there is a substantial component that moves into Russian waters) will lead to: 1) an incorrect estimation of biomass (via incorrect auditing of fishing effects to the stock), 2) potential for localized stock depletion, 3) misperception of stock status (i.e., stock moving outside of boundary can be incorrectly inferred as reductions in biomass) and masked localized depletion (i.e., system spawning biomass is stable, but small spawning populations are extirpated), and 4) the potential for over and underutilization of the resource.

# Question 3

There are several complications that may arise from amending the current strategy to the proposed biological structure. Firstly, revising the current population structure and managing it in the proposed fashion (i.e., accounting for movement dynamics and natal homing) will require vast amounts of data that may not necessarily be feasible due to concerns with data limitations and model overparameterization and stability. In particular, accounting for natal homing dynamics here would require stock-specific information (i.e., population origin) from mark-recapture data (e.g., utilizing some variation of the overlap model; Vincent et al. 2017). Furthermore, potential difficulties in data collection protocols may arise from treating the GOA region as two separate stocks. For example, if differential harvest pressure occurs (which it likely does) between the EGOA and WGOA, sampling protocols will dictate increased effort towards data collection for heavily harvested areas, which may impede estimation of spatially explicit parameters. To support the proposed approach, more resources would need to be allocated towards sampling these 4 different stocks adequately.

Assuming that the proposed strategy (i.e., spatial assessment) and realignment of biological structure is feasible, there can be different implications pertaining to harvest quotas. In particular, if certain stock components have small population sizes and receive substantial subsidies from other stocks due to mixing, there is potential for management advice that suggests minimal fishing effort towards stocks providing the subsidy, while allowing for high fishing mortality to the receiving stock (Goethel and Berger 2017; Bosley et al. 2019). This has the potential to result in a substantial displacement of fishing effort and inequitable fishery outcomes (i.e., harvesters may have to travel much further from port to be able to fish) and is generally inconsistent with how management and fisheries operate. I recognize that the current proposed realignment of boundaries generally refers to Alaska as a whole. To cover my bases, if boundaries were to be delineated between Japan, Russia, Alaska, British Columbia, and coastal Washington as a whole (i.e., implications on an international scale), the impacts discussed above would likely result (no harvest in certain regions) in substantial political tension, and potentially… World War III given the current political climate (I would have to fight for America!).

Considering current management constraints, several approaches can be implemented to ensure population resilience, while still maintaining equitable fishery outcomes. Firstly, it is possible that the current methods for allocating catches to different regions/stocks are appropriate (i.e., catch-cascading; Spies et al. 2015). However, instead of simply utilizing the survey index to allocate catches, it may be more appropriate to allocate catches utilizing data from the fishery during the winter, which may better reflect differences in spawning components. Alternative approaches could consider combining both fishery-independent and dependent data to develop a more representative index of stock-specific biomass, although there are other complications that need to be considered there. In addition to catch allocation-methods, utilizing strategies that protect the weakest component of the stock from fishing could also be employed, but has the potential to result in underutilization of yield as well as unnecessary fishing effort being imposed upon populations that are more productive (Kerr et al. 2014). The use of spatial and/or temporal closures could also be utilized to displace fishing effort and protect spawning contingents, which would not require the use of a fully spatially explicit assessment procedure. Furthermore, alternative approaches that could also be considered include managing high fishing effort areas separate from lower fishing effort areas. In particular, some studies have found that this strategy can be useful for reducing the probability of stock overexploitation, when compared to an approach that manages both high and low fishing effort regions as a single unit, because the latter approach masks the potential for localized depletion (Spies et al. 2015). Lastly, management approaches could also utilize empirical reference points to protect biocomplexity and resilience. Specifically, indices such as the Highest Density Area (HDA) reference point have been demonstrated to exhibit a concave relationship with spawning biomass, and seeks to reflect the erosion of spatial structure (density hotspots). These empirical reference points can readily be incorporated as limit or target reference points within harvest control rules commonly utilized, and could also be a promising approach to address concerns with population structure (Reuchlin-Hugenholtz et al. 2016). However, the appropriateness and robustness of each of the approaches discussed above will require need to be thoroughly evaluated within the context of a spatially explicit management strategy evaluation (Cadrin et al. 2023).

# Question 4

## Outline

Steps 1 through 4 synthesizes all available information about the stock structure and is meant to be an iterative process and allow for review and flexibility in redefining stock structure and boundaries (iterated every several years).

1. Synthesize all available data of the stock (e.g., genetic differences, phenotypic differences – can be identified via genomics, natural markers, larval IBM modelling),
2. Identify stock boundaries,
3. Identify spatial structure within the stock (e.g., metapopulation, spatial heterogeneity, fleet structure),
4. Develop hypotheses and drivers of movement dynamics (e.g., ontogenetic, time-varying, seasonal migrations),

The following steps will be an iterative process based on stakeholder and expert feedback, which will also consider the available data to represent the proposed dynamics.

1. Define population structure for the assessment utilizing information about stock structure, spatial structure, and stock boundaries (e.g., metapopulation, spatial heterogeneity),
2. Define temporal resolution of the model based on fishery and biological dynamics (e.g., seasonal movements, discrete fisheries),
3. Decide how recruitment should be modelled, which should be guided based on the population structure (e.g., spatial apportionment with global recruitment for spatial heterogeneity population structure),
4. Parameterize the gear structure of the model (e.g., whether different gears share the same selectivity patterns),
5. Parametrize dispersal movement dynamics utilizing hypotheses developed in step 4 (e.g., natal homing and the potential for skipped spawning, ontogenetic movements, no movements post-settlement),
6. Decide on how demographic variation should be represented (e.g., are they area-specific or stock-specific (spatial-heterogeneity vs. meta-population), do they vary across space or time?)
7. If competing hypotheses exist, develop additional models utilizing this framework,
8. Compare different spatial models with varying hypotheses as well as non-spatial models (e.g., population trajectories, *a priori* hypotheses and knowledge, model fits),
9. Consider how reference points should be defined (e.g., area-specific, system-wide, equilibrium vs. non-equilibrium),
10. Simulation test the developed model frameworks against higher resolution spatial models (e.g., spatially explicit IBMs, models with more complex spatial structure),
11. Communicate results with scientists, and stakeholders, while implementing transparent assessment frameworks (code-sharing and detail decision points). Iterate model parameterizations and validate models utilizing knowledge from stakeholders and community members.

## Conceptual Model

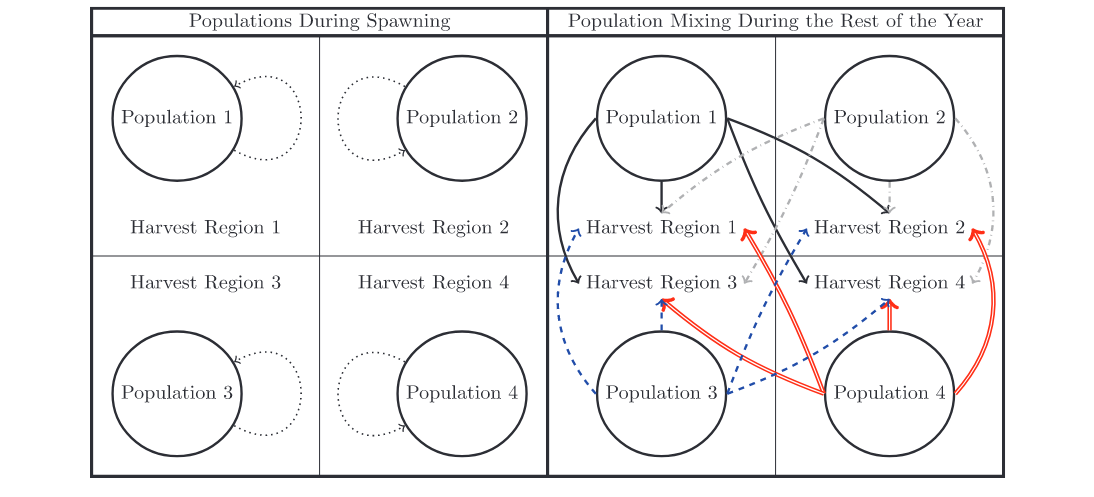


Figure 1. Conceptual model of the ideal spatial structure and assessment framework for Pacific cod (stolen from Vincent et al. 2017; somehow this nicely fit what I wanted…). Here, 4 stocks and harvest regions are defined, representing the Bering Sea, Aleutian Islands, western Gulf of Alaska, and the eastern Gulf of Alaska. During the first quarter of the year, individuals return to their population to spawn. During the remaining 3 quarters, individuals mix within different harvest regions. Within each harvest region, 3 separate gears would exist, which include pot gear, trawl gear, and longline gear.

## General Parameterization

Here, a spatially explicit but stratified approach will be utilized (single sex). This model generally mimics the spatial overlap model, where individuals home to their original population at the start of the year and are able to mix during the remainder of the year (Vincent et al. 2017). 4 stocks/populations will be defined, which also correspond to the 4 harvest regions, which are the BS, AI, WGOA, and EGOA. Given that individuals return to their natal origin to spawn, the population structure here represents a metapopulation, where density dependence is localized. In most spatial models, is generally ideal to have flexible movement parameterizations to minimize potential biases, which I will also follow here (Goethel et al. 2021; Bosley et al. 2022). Thus, in an ideal scenario, we would allow for the estimation of stock, age, and time-specific movement parameters. For a species like Pacific cod, it is likely that movement varies across ages and years (annual), given their recent expansion into the Bering Sea, as well as the potential for ontogenetic movements (Laurel et al. 2009; Spies et al. 2020). Furthermore, it is also generally well known that spatial heterogeneity can arise due to differences in fishing effort as well as fishery selectivity patterns (Cadrin 2020). As such, in an ideal world, this model will represent gear and area specific harvest patterns, where separate selectivity patterns and fishing mortality multipliers are estimated for each region. Given the metapopulation structure of this model, vital rates will be estimated on a stock-specific basis.

For information or analyses that may help inform the appropriateness of this parameterization, this would include any information that pertains to stock structure, spatial structure, and spatial boundaries. In particular, information such as genetic and natural markers (e.g., parasites, otoliths), larval IBM studies coupled with oceanographic drivers and *a priori* knowledge of oceanographic features, tagging and movement data, and evaluation of fishery characteristics (size and age-structure, and differences in abundance trends) can all be utilized to understand whether the proposed parameterization is appropriate. The use of genetic and natural markers, larval IBM studies, and knowledge of oceanographic features can all help understand whether the underlying stock structure, spatial structure, and stock boundaries are adequately defined. Additionally, this can be coupled with analyzing fishery or survey data (e.g., age composition or abundance indices) utilizing multivariate regression tress to provide a further understand the appropriateness of spatial and gear delineations (Lennert-Cody et al. 2010, 2013). Analysis of movement and tagging data outside of the stock assessment can similarly inform the appropriateness of the proposed population structure but can also help inform the degree of flexibility that may be required for parameterizing movement dynamics (e.g., if movements are consistent across time).

Several types of data are needed to inform such a complex model. Notably, to adequately estimate natal homing and stock-specific dynamics, stock-composition data for ages and tagged individuals are required (annual). Thus, some form of genetic information is required in this model. Similar to many integrated assessment frameworks, catch data, age-composition data (gear, year, and region specific), and survey abundance indices are required for this model. Furthermore, growth data (length, age, weight) should also be available for all regions and stocks in this model formulation. In a perfect world, it would also be ideal to integrate abundance estimates from genetic tagging studies, which could help inform a variety of processes (mortality, abundance, stock origin), while circumventing the need to estimate nuisance parameters that are commonly necessary for utilizing convention tag data (tag mortality, shedding, mixing) (Bravington et al. 2016; Trenkel et al. 2022).

However, the described framework above requires an abundance of data, and may suffer from issues related to model overparameterization. Thus, several simplifying assumptions may need to be made. For example, instead of specifying gear and area specific parameters to describe selectivity patterns, it may be necessary to constrain estimation procedures by sharing selectivity parameters across areas. Alternatively, another constraint that could be imposed could include aggregating gear-specific information within an area, but estimating area-specific selectivity parameters. With respect to movement parameterizations, constraints could be placed by allowing age and year parameters to vary as discrete time-blocks, utilizing state-space implementations to reduce the number of effective parameters estimated, or imposing a functional form for age-specific movement estimates (or a gravity model). Movement parameters could also be estimated external to an assessment model and be utilized as fixed inputs or priors to further constrain estimation if necessary. Furthermore, if tag data are not available, movement parameters can still be estimated, although these estimates can be highly confounded with recruitment estimates (Hulson et al. 2013; Bosley et al. 2022). Additionally, if data are not collected on the appropriate scales, it may be necessary to allow for flexible likelihood functions that are able to fit to both spatially aggregated and spatially explicit data. The burden on estimating tag parameters (e.g., tag shedding, mortality) could also be circumvented by conducting double-tag studies when tagging operations are underway and utilizing these external estimates to reduce estimation complexity. It may be necessary to fix certain demographic parameters, particularly for those that might not exhibit strong spatial or stock-specific variation (also may just need to make a simplifying assumption for parameters like natural mortality).

A key benefit of a spatially explicit model is that it estimates population/area-specific trajectories, which can allow the explicit monitoring and management of specific stocks/areas. As such, stock status should be reflected on the meta-population level, where population spawning biomass relative to a population specific reference point are derived. If explicit stock-recruitment functions (i.e., those with depensation and/or compensation) are estimated, reference points related to Fmsy can be derived (using the approach of Sissenwine and Shepherd 1987). However, if the estimation of such functions is not feasible (i.e., no production function here) then spawning potential ratio (SPR) proxies should be utilized instead, where the level of SPR likely depend on the resiliency of the stock. The most appropriate level of the SPR proxy should be evaluated using management strategy evaluations. Irrespective of whether Fmsy or SPR proxies are utilized, estimated quantities from the spatial framework can be utilized to simulate population dynamics forward, until the population reaches some equilibria. Concomitantly, combinations of stock/region and gear specific values of fishing mortality can be utilized to the ideal combination that either maximizes system wide yield (i.e., Fmsy) or achieves some desired level of SPR (e.g., F40%) (as in Goethel and Berger 2017), although note that some recent approaches do not require running the population to equilibrium to define reference points (employs an iterative search algorithm coupled with deterministic equations) and yields similar results (Kapur et al. 2021).

# Question 5

Considering my current research, with a focus on fleets, gears, and selectivity, I do not necessarily believe it is imperative to utilize a fully spatially explicit assessment model to adequately estimate population/system-wide biomass or provide robust management advice. Studies have shown that single-area approaches and spatially implicit approaches (i.e., fleets-as-areas) can adequately approximate system-wide level biomass and can still result in robust management advice even when spatial heterogeneity exists (Punt et al. 2017). Single-area or spatially-implicit approaches can perform robustly even in the presence of substantial spatial dynamics if sample sizes (i.e., overdispersion) particularly compositional data are re-weighted (deals with unmodelled processes and reduces the influence of fitting composition data to other data sources such as abundance indices) or if flexible time-varying selectivity approaches are utilized (because of changes in availability as well as the potential for dome-shaped dynamics under conditions of spatially-varying fishing mortality) (Hulson et al. 2013; Lee et al. 2017). Some newer approaches that could potentially be of utility in the context of accounting for spatial and movement dynamics under a single-area assessment framework includes the estimation of process variance for the exponential mortality model, although the robustness of this approach remains untested. However, these approaches are unable to detect the presence of localized depletion, which may render them inadequate if localized depletion is of great concern (it does not appear to be in Pacific cod). To understand whether the current assessment and management structure is adequate for Pacific cod, an analyst could conduct a spatially explicit management strategy evaluation. Here, the operating model would attempt to incorporate all of the existing hypotheses and complexities involving population structure and movement dynamics, as well as fishery dynamics (which I have described in previous responses). Data would then be generated from the operating model, which can be aggregated up to match the current management structure, where biomass and management advice are estimated for each year (or using some biomass index and applying some white noise; e.g., Punt et al. 2008; Spies et al. 2015)), and recommended catch levels are reapplied back to the operating model. Performance of the current management structure could then be evaluated by understanding metrics such as the probability of localized depletion. Alternative harvest strategies could also be simultaneously evaluated in the context of a single-area model, if the current management strategy is found to be undesirable.

# Question 6

Pacific cod are highly sensitive to their prevailing environment, which has resulted in various changes in their population dynamics. Within the context of spatial dynamics, Pacific cod are likely to colonize and expand into higher latitude habitats under scenarios of climate change (Spies et al. 2020; Thorson et al. 2021), likely in search of thermal refugia, but also in response to changing distributions of prey species. These changes in movement dynamics are likely to have important implications for traditional surveys that occur in the EBS and NBS. In particular, if individuals exhibit cross-boundary movement into other regions, it is likely that single-area assessments for Pacific cod, will either be severely misfit to abundance indices, predict large incoming recruitment events, or predict a large mortality event (which is not uncommon for a species like Pacific cod). These changes and erosion in population structure will ultimately lead to a misperception, which could result in over-utilization in the region where incoming recruitment events are predicted to be large or result in under-utilization in the region where directional movement into the receiving area occurred (similar to the case study of Georges Bank winter skate; Frisk et al. 2010). Obviously, an approach to account for such changes in distribution under a single-area assessment framework would be to allowing for time-varying catchability processes (Hulson 2023; Rogers et al. 2024), although it would be prudent to understand the mechanisms driving a reduction in catchability to avoid spurious explanations by the model (e.g., ensuring that changes in abundance are due to changes in distribution and not mortality).

The collection of several new novel emerging data types could potentially help better understand such dynamics under climate change. Specifically, the use of pop-up satellite electronic tags, which provides fine-scale movement data, could help understand whether Pacific cod released from specific spawning populations are moving outside of the management domain during specific periods of the year, and hence, outside of the traditional survey domain. Coupled with electronic tag information, the collection of depth, temperature, and other auxiliary environmental variables could help better understand how Pacific cod movement dynamics respond to changes in environment, which can be utilized to parameterize preference functions for movement in the context of a spatial model. However, beyond the context of a spatial model, fine-scale temperature and movement data could help analysts understand whether such as relationship exists, which can be linked to catchability parameters within a traditional single-area assessment. The use of autonomous sampling could also be of potential value in developing abundance indices for Pacific cod (i.e., acoustic surveys), particularly if individuals move into model domains that are not easily accessible by traditional surveys. In the context of political boundaries, if individuals were to move outside of Alaska during specific periods of the year, the deployment of passive high-resolution echosounders could potentially be of value in understanding the degree of movement outside of the political domain (e.g., into Russia). Ultimately, the continued collection of high resolution tag information and understanding of distribution shifts in response to climate will allow the feasible implementation of spatio-temporal models that account for more fine-scale spatial dynamics (Cao et al. 2020; Thorson et al. 2021), which could supplement or complement traditional assessment and management tools that are currently utilized.

Under climate change scenarios, there is potential for high uncertainty in model-based estimates from stock assessments. Furthermore, it is not always feasible to explicitly model complex spatial dynamics and/or climate impacts. Thus, robust approaches that adequately account for such uncertainties are necessary for the robust management of Pacific cod. Currently, all three stocks are managed utilizing Tier 3 methods, where the harvest control rule following a sloping threshold pattern, where limit biological reference points are based upon B20% and F20% and target reference points are based on B40% and F40%. However, it is has been demonstrated that these limit and target reference points might not necessarily be suitable for all species (Clark 2002; Punt et al. 2008). As such, one approach to confronting uncertain dynamics and climate impacts could involve better optimization (e.g., increased uncertainty buffers, reduced fishing mortality, increased levels for reference points) of target and limit reference points within the sloping harvest control rule through simulation testing via management strategy evaluations (Free et al. 2022). Additionally, recent studies have shown that despite certain species have an abundance of data, they can potentially be resistant to the use of complex age-structured models (Legault et al. 2022). This phenomenon could potentially increase in frequency if climate impacts conflict with model assumptions (e.g., closed population, but emigration occurs due to distribution shifts) and there may not be adequate time for further explorations of model structure. Thus, in line with recommendations with Free et al, 2022, empirical rules (e.g., survey indices, HDA index) could be developed to support the traditional sloping threshold control rule, which could potentially be reliable, in the case that age-structured stock assessments fail to pass the review process and model-based data-rich rules are deemed unreliable. In a similar vein, investment in the collection of novel data sources (i.e., close-kin mark recapture studies) could also serve as a robust index for developing empirical/hybrid harvest control rules (Trenkel et al. 2022), in situations where complex models fail to pass review. Furthermore, the continued investment and collection for ecosystem information will allow us to better understand the various environmental mechanisms that impact Pacific cod in the Northeast Pacific, which may facilitate more proactive, rather than reactive management procedures (Barbeaux et al. 2020). As a final suggestion, the current management plan for Pacific cod should include: 1) provisions to ensure that stock structure and boundaries are re-evaluated on a regular basis (Cadrin et al. 2023), 2) include conditions and regular re-revaluations of the current harvest control rule, and 3) include specifications and rules that account for exceptional circumstances (e.g., high mortality events). Ultimately, the development of adaptive assessment and management procedures will need to be thoroughly tested via simulations utilizing a variety of scenarios to ensure that conservation, management, and harvest objectives are met.

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