Linking Crustacean Life History to Fishery Management Controls and Reference Points

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Abstract:

Management of crustacean fisheries is often data-limited, and techniques used in finfish fisheries are often inappropriate for crustaceans due to life history differences. Limitations in modeling capacity and data-availability make it difficult to determine the status of crustacean stocks using model-based biological reference points (BRP), but BRPs are a key component of successful fisheries management. Using crustacean fishery case studies depicting model-based and empirical management strategies, we synthesized the current state of crustacean fisheries management with respect to data-availability and use of management controls. Input and output controls can be successful with supplemental BRPs, but whatever methods are used must explicitly consider species' unique life history characteristics. In data-limited fisheries, output controls can effectively conserve a species under high levels of exploitation. Implementation of discrete BRPs can improve sustainability of both emerging and data rich crustacean fisheries, to make these quantitative metrics a valuable tool for crustacean management globally.

Keywords: Crustacean Fisheries, Fisheries Management, Biological Reference Point, Management Controls, Stock Assessment, International Fisheries

Introduction

Crustacea are one of the most diverse groups of aquatic animals found in a wide variety of habitats and locations across the globe. Crustacean species contribute ~8% of the total world seafood supply and ~23% of global fisheries value in 2019, with roughly half from wild stock harvesting and the rest from aquaculture (FAO 2022). Since 1990, crustacean fisheries landings nearly doubled as a proportion of global landings, from 4.4% to 7.8%, with overall global landings remaining relatively static as finfish landings decreased (Boenish *et al*., 2021; FAO 2021). While increasing landings from China were the biggest contributor to global growth, global crustacean landings also increased (Boenish *et al*., 2021). Crustacean species historically kept a high market value, thereby leading to rapid development of fisheries and need for active management to sustain long-term harvesting.

Research on crustacean stocks has revealed key morphological and physiological differences between finfish species and crustaceans that influence stock assessment and the application of management controls related to growth, catchability, and migratory parameters (Smith and Addison, 2003; Fogarty and Gendron, 2004; Punt *et al.*, 2013). To molt, crustaceans increase in size in incremental steps, rather than continuously like finfish (Chang *et al*., 2012). Compounding the complexity of molting, crustaceans lack internal permanent hard structures, such as vertebrae or otoliths like finfish, so age of crustaceans cannot be estimated using traditional finfish methods (Penn, 1984). Crustacean movement and molting are often sensitive to environmental factors (Azra *et al.* 2018), and catchability can be cyclic or inconsistent, not necessarily from changes in stock abundance. To properly assess crustacean stock status, a long time series of data is needed to link different life history stages to subsequent catch. Adults of high-value crustacean species like lobsters, crabs, and shrimp often protect eggs until hatching, so selective conservation of large fecund individuals can be an effective management strategy (Baeza *et al*., 2016; Dickinson *et al*., 2006; Thiel, 2003). Pot and trap gear is commonly used in large crustacean fisheries and discards from pot and trap gear have a much lower release mortality than those caught in trawl fisheries (Stevens, 2021). Many decapod crustacean species (e.g., American lobsters, tanner crabs, red king crabs) survive after being discarded from their respective trap fisheries (Smith and Howell, 1987; Stevens, 1990; Urban, 2015). These differences often result in management measures and strategies that were designed for finfish being ineffective or impossible to apply to crustaceans.

Biological reference points (BRPs), harvest control rules (HCR), and input and output controls are comprehensive management tools used in concert as a best practice for global fisheries management (Gabriel and Mace, 1999; Collie and Gislason, 2011). BRPs are limit or target indicators used as a benchmark to measure stock status (Williams and Shertzer, 2003). For many crustacean fisheries, information is lacking for stock-recruitment relationships and other model parameters that are often used to manage finfish fisheries (Smith and Sainte-Marie, 2004).

Empirical reference points can be derived from direct observations, such as catch, fishing season length, individual size, and fishing effort (Punt *et al*., 2001; Clarke and Hoyle, 2014). While empirical reference points may be useful for data-poor fisheries, most reference points used in fisheries management are model-based, because empirical approaches lack the theoretical rigor of model-based approaches (Hilborn, 2002). Model-based reference points can be used to estimate fishing mortality or biomass-based reference points typically used in management, whereas empirical reference points are only proxies of such reference points (Gabriel and Mace, 1999). HCRs are predetermined rules or guidelines that limit the amount of fishing for a target species to conserve stock status or react dynamically to changes in the stock (Apostolaki and Hillary, 2009; Punt, 2010). HCRs are often based on BRPs, using either empirical or model-based BRPs as indicators of overall stock status (Kvamsdal *et al*., 2016; Punt, 2010). Output and input controls can be used to constrain fisher behavior and limit landings. Output controls restrict what fishers can land, such as a total allowable catch (TAC) or quota, or individual measures like minimum and maximum size or sex-selective catch (Morison, 2004). Input controls are used to constrain fishing effort rather than catch, and can target fishers, as well as spatial or temporal restrictions (Morison, 2004). Due to challenges of data collection and assessment for crustacean fisheries, utilizing and applying theory-based BRPs has been a challenge for management. Crustacean reference points must be set for each individual stock based on life history characteristics and localized environmental factors.

To review BRP and HCR use in crustacean fisheries, we assessed data gaps in crustacean fisheries research identified by an international Crustacean Task Force (CTF), an interdisciplinary working group of crustacean fishery scientists and managers from four top crustacean fisheries countries, the United States of America, China, Indonesia, and the Philippines, that convened from August 2020 through December 2022. We focused on examples from two countries, Indonesia and the United States, where a mixture of input and output controls have been used to manage highly valuable crustacean fisheries. Across fisheries, stock assessment metrics like BRPs and HCRs were applied with varying levels of data availability. We focused on specific crustacean fisheries in these countries to illustrate the utility of input controls to control a fishery, and shortcomings of current BRPs and HCRs in practice, while suggesting ways to improve applicability and management of these important resources. We propose that management of valuable decapod crustacean fisheries has been successful without output controls because of resilient crustacean biology and application of precautionary spawner protections. While many crustacean fisheries are data limited, stable fishery landings suggest that input controls can be effective for sustaining some stocks, in contrast to historical finfish fisheries managed without formal stock assessments.

Methods

Nine case studies from eight of the most valuable crustacean fisheries in Indonesia, Greenland, and the United States were selected by experts from countries within the CTF (Fig. 1). Case studies represented differing management, fisheries, and assessment strategies of high current or historic landing value. Each case study was based on information and perspectives provided by fishery experts within the working group with direct experience studying or managing the fishery. Experts were chosen based on their comprehensive knowledge of the fishery and management structure. The review relied on unique knowledge and access to information generally not available to a standard literature review. A template was completed for each case study expert to inform a detailed report on each species (supplementary materials). Case studies included American lobster (*Homarus americanus*- USA), snow crab (*Chionoecetes opilio*- USA), Dungeness crab (*Metacarcinus magister*- USA), blue crab (*Callinectes sapidus*- USA), brown shrimp (*Farfantepenaeus aztecus*- USA), northern shrimp (*Pandalus borealis*- USA, Greenland), blue swimming crab (*Portunus pelagicus*- Indonesia), and seven Indonesian spiny lobster species. Using information provided in the template, we described the state of each fishery from a biological and management point of view.

1. American lobster is the highest valued single species fishery in the United States (NOAA 2023), with a long history of harvest and management and a robust stock assessment with highly available data. This species was chosen to explore how steadily increasing abundance of a species was achieved as a model for other crustacean species.

2. Dungeness crabs are a valuable harvested species across the Northeast Pacific, with no formal stock assessment. The robust fishery is managed by trend-based assessments, which illustrates high fishery success using a data-poor approach.

3. Blue crabs are harvested throughout their range across the eastern seaboard of the United States. The review was restricted to the Chesapeake Bay stock, which supports a productive commercial fishery under a distinct management plan.

4. Snow crab has supported a historically robust fishery and has a large biological sampling and stock assessment program. Recent extreme losses of certain sizes have made this fishery a case study of managing unexpected outcomes for an otherwise well described stock.

5. Indonesia's blue swimming crab (BSC) has a very limited fisheries history. Catches are reported from most Indonesian waters, commonly using collapsible traps and bottom-set gillnets. Most information came from either Indonesian Fisheries Management Area (FMA) 712 or Java Sea, which accounted for 40% of national production (Ernawati *et al*., 2021). This case study represents an example of a data-limited crustacean fishery that has a relatively short exploitation history.

6. Indonesia is host to seven species of spiny lobster, scalloped spiny lobster (*Panulirus homarus*), ornate spiny lobster (*P. ornatus),* pronghorn spiny lobster (*P. penicillatus),* longlegged spiny lobster (*P. longipes,* stripe-leg spiny lobster (*P. femoristriga),* painted spiny lobster (*P. versicolor)* and mud spiny lobster (*P. polyphagus),* which are collectively managed as spiny lobster. These species comprise a valuable fishery with a long history of artisanal harvest for consumption and juvenile or *puerulus* capture for aquaculture, however these harvest methods pose distinct challenges to data collection as opposed to a more centralized fishery.

7. The northern shrimp fishery in the Gulf of Maine has been under moratorium since 2014 due to low abundance and persistent recruitment failure. The stock is still subjected to consistent stock assessment analyses and illustrates how a TAC managed crustacean fishery can still collapse when life history and changing environmental conditions are poorly considered.

8. Greenland northern shrimp is managed using comprehensive BRPs and TAC, which provides an important contrast to the Gulf of Maine northern shrimp fishery.

9. Brown shrimp are part of a suite of species that comprise the larger Gulf of Mexico shrimp fishery. The rapid life history, large harvest, and highly variable landings contrast with Gulf of Maine (GoM) and Greenland northern shrimp fisheries.

Reference points common to finfish fisheries management were distilled from available literature (Table 1). BRPs we expected to see applied across case studies were based on general use in fisheries management with reference point definitions. Case studies were compared in available data to stock outputs, with consideration of novelty and size of the fishery when making recommendations for BRP and HCR implementation. Case study template responses were reviewed and distilled into outlines (supplemental materials).

To build a cohesive series of case studies, a template was developed and completed by each case study expert. The case study template solicited general species and fishery information, and the history and current status of management efforts. Questions were organized within four general subgroups: species biology, fishery behavior, management history, and data and management complexity. Case studies were described within a framework of overall data availability, a metric of landings time-series length, overall biological data availability from field sampling, field and laboratory research, and selectivity.

To evaluate the influence of crustacean biology on management, life history information was thoroughly described (Table 2). Data pertaining to species biology covered the range of life history characteristics of each species, management concerns about the fishery, or conservation of the species relevant to species biology. Biological information was derived from data collected by fishery independent and fishery dependent monitoring programs that varied in terms of biological data collection capacity among fisheries.

A subgroup of questions about behavior of fishery participants and diversity of fishing fleets explored the application of harvest control rules to each fishery (Table 3). Each fishery was described in terms of season, effort, industrial scale, gear type, and vessel type, as background for management applications. The history of each fishery included the period for application of management frameworks (supplemental materials).

Management history included a basic overview of stock status, assessment model, recruitment trends, and climate susceptibility, combined with regulatory measures applied and approximate time series of fisheries management (Table 4). Data and management complexity described current status of stock assessment and existing data for the fishery, to recommend applicable reference points. Management structure varied widely among species and nations harvesting the same species. Experts were asked to describe management structure and presence or absence of existing fishery management plans, BRPs, and harvest control rules (HCRs). Advanced data collection programs were not always integrated into management outcomes, so experts were asked to describe the framework for applying research outcomes to management decisions.

Each case study species was graded according to the scale and intensity of research, collectively weighed and ranked by case study experts. Case studies were organized across a low-medium-high scale of data availability (inclusive of time series length and biological data complexity). Recent trends in landings for each case study were used to describe fishery stability and stock status. Reference point use was characterized on a low-moderate-high scale, with empirical reference points at the low end. Moderate use required application of at least one additional non-empirical reference point. With three or more reference points, species were considered to be well described relative to other crustacean fisheries. Data time series did not ideally fit BRP integration, so fisheries were ranked in relation to other case studies, as relatively high or low complexity. After combining data availability with recent trends in landings and formal application of BRPs, we recommended varying levels of urgency in BRP application depending on unique circumstances of each fishery. Our recommendations were moderated for species such as Dungeness crabs and American lobster, for which prolific input controls successfully maintained stable stock status.

Results

Species with shorter time series and high-effort biological sampling (e.g., snow crab) had greater data availability than species with a long time series of landings and poor biological sampling (e.g., Dungeness crab; Fig. 2). Stock status and landings time series were positively correlated for all species, except Indonesian BSC and spiny lobster, for which landings increased despite low stock abundances due to increasing fishery exploitation. For Dungeness crab, landings trends were the only metric of stock status.

Crustacean species all molted once or more annually, but at different times of year, and varied widely in longevity, recruitment age, and instantaneous natural mortality (Table 2). Species depth distribution varied widely across case study species, with thermally driven seasonal shifts influencing changes in the distribution of fishing effort. Lobster species generally lived the longest, recruited to fisheries at the oldest age, and suffered the lowest instantaneous rates of natural mortality. In contrast, shrimp species generally lived the shortest lives, recruited to fisheries at the youngest age, and suffered the highest instantaneous natural mortality. Dungeness crab and snow crab were intermediate but closer to lobster species in life history traits, whereas blue crab and blue swimming crab were intermediate but closer to shrimp species in life history traits.

Crustacean fisheries varied widely in landings and value, and were managed with input controls, output controls, and both input and output controls (Table 3). Landings ranged from less than 10,000 tonnes for spiny lobster to more than 110,000 tonnes for northern shrimp. Value ranged from less than USD$6-million for brown Shrimp to nearly USD$700-million for northern Shrimp, with other species ranging USD$132–530 million. Fishery methods were mostly passive (fixed-position) gears (pots, gillnets, trotlines, hoop nets), with only brown shrimp and northern shrimp harvested by active gears (trawls).

Stock assessment models, stock status, recruitment variability, and thermal tolerance varied widely among crustacean fisheries (Table 4). Size and age-structured models were the most complex methods used for stock assessment (American lobster, blue crab, brown shrimp, northern shrimp, snow crab), with surplus production models also used for more data-limited species (BSC, spiny lobster). No formal assessment is available for the Dungeness crab fishery. Stock status was increasing for American Lobster, variable but stable for blue crab and Dungeness crab, over-exploited or declining for BSC, brown shrimp, and northern shrimp. Reported recruitment was variable for all species, but especially for Dungeness and snow crab. Thermal preference was strong for all crustacean species, and a driver of spatial distributional changes for all species.

Although all case study species were managed with empirical reference points, more advanced biological stock status indicators were not uniformly applied across fisheries or within individual countries (Table 5). For some data-rich, well-studied species, like American lobster, BRPs were not used in fishery management plans (ASMFC 2020). For data-poor species, like Indonesian BSC and spiny lobster, BRPs were included more often in fishery management plans than for data-rich fisheries. Therefore, the scale of BRP use was not related to data availability in either direction, and did not indicate complexity of fishery management plans. The now-closed northern shrimp fishery in the GoM had a similarly long data time series and stock assessment schedule as the active Greenland fishery, but management of the GoM stock used only empirical BRPs, while ICES and NAFO managed the West Greenland stock with a suite of reference points (ASMFC 2018, Burmeister and Rigét, 2021). Value of the Greenland fishery could have driven implementation of more robust reference points, but American lobster, blue crab, and Dungeness crab were also high-value fisheries with little BRP application, which suggests that fishery value was a poor predictor of BRP use.

Discussion

Within case studies we examined, only the Greenland northern shrimp and snow crab fisheries were regulated using a TAC output control (Burmeister and Riget, 2018; Szuwalski *et al.* 2023), which is one of the most common approaches to regulate harvest (catch composition and volume) of finfish fisheries (OECD 2022). Indonesian BSC and spiny lobster used an MSY-proportional TAC as a harvest goal to determine if overfishing was occurring. While formal TACs are not commonly used in decapod crustacean fisheries, other forms of output controls such as minimum size and sex-specific retention are routine (National Research Council, 1999). Use of alternative output controls was a function of crustacean biology and fishery behavior. Capitalizing on decapod crustacean high post-release survival (Rodrigues *et al*., 2015; Fox *et al*., 2020; Barnes *et al*., 2022), minimum and maximum sizes can be used to regulate fishery selectivity toward specific cohorts within target species populations. These specific rules allow fisheries to either target high-value size classes or protect specific size classes of spawning stock, depending on fishery management goals, while high survival reduces discard mortality. Sex-specific catch is possible for crustacean fisheries on species that are either sexually dimorphic in morphology or behavior. For example, commercial fisheries for Dungeness, snow, and blue crab in the United States target males because of sexually dimorphic growth that leads to larger male size, which also have a higher landed value per individual, and incidentally protects spawning females (Carver *et al*., 2005; Garber-Yonts and Lee, 2020; Richerson *et al*., 2020). External sexual indicators common in decapod crustaceans (Ozawa, 2013), in conjunction with high discard survival, allow sex-selectivity that is not possible for most finfish fisheries. Northern shrimp fisheries in Maine and Greenland target seasonal sex-specific aggregations of large female shrimp (ASMFC 2018, Burmeister and Riget, 2018). Similar fishery behavior based on sex-specific seasonal aggregations of a target species enables precise management through seasonal fishery input controls. For fisheries that relied on output controls, a combination of sex selectivity, size restrictions, and protection of egg-carrying females interacted with crustacean spawning biology to increase survival of pre-recruits. High pre-recruit survival safeguards recruits from a limited number of spawning adults to increase resilience of these species to high fishing pressure.

Input controls were the most common form of fishery control among case studies we examined, especially for fixed gear fisheries and fisheries where a TAC was not implemented. For all case studies we examined, CPUE was an empirical reference point, so management of the number of sea days or deployable gear could be used to regulate landings (ASFMC 2020). Input controls as an exclusive fishery management tool have failed for many finfish fisheries, with management relying more on output controls, such as TAC, for most heavily commercially exploited fisheries internationally (OECD 2022). Output controls regulate allowable harvest, so provide a more direct mechanism on harvest than input controls (Pope 2009). However, output controls, such as TAC, may require higher levels of data collection, availability, and type for development and enforcement (FAO, 1997). Among case studies we examined, crustaceans were well managed without TAC. For example, some shrimp species have been successfully managed with TAC (Ziegler *et al*., 2016, Burmeister and Riget, 2018), although recruitment patterns and exogenous climate-forced environmental changes must be understood to avoid stock failure, as for Gulf of Maine northern shrimp (ASMFC 2018). We found that a hybrid approach of input controls with continuously integrated BRPs has worked comparatively well for conserving crustacean case study stocks, thereby highlighting the apparent robustness of crustacean fisheries despite challenges of applying management to their unique life histories.

We found little use of reference points among case studies we examined that did not rely on a formal TAC, likely because input and non-TAC output controls were effective for managing decapod crustacean fisheries. In finfish fisheries, indicators typically focus on fishing mortality, recruitment, or biomass, whereas for crustacean fisheries, a correlation with environmental factors can be more predictive (Caddy, 2004). Biological reference points for the Shark Bay and Cockburn Sound blue swimmer crab (*Portunus armatus*) and the Exmouth Gulf and Shark Bay brown tiger and western king prawns (*Penaeus latisulcatus*) in Western Australia were developed based on stock-recruitment-environment relationships (Caputi *et al*., 2021). Understanding such relationships enabled BRP informed harvest strategies to account for specific biological and environmental information. While a range of methodologies are used for estimating biological reference points for finfish species, no formal toolbox can be used for crustaceans. For example, estimation of BRPs for some crab fisheries is complicated by the fact that only males are caught, and mostly driven by environmental factors rather than density-dependent responses (Siddeek, 2003). BRPs could be used for crustacean fisheries that are often heavily exploited with stock-recruitment relationships that favor large highly fecund brood stock (Penn *et al*., 2018). We found successful crustacean fisheries like Dungeness crab and American lobster were managed based on trends in abundance or landings without BRPs, although BRPs could be used to inform management rules. Blue crab fishery management uses input controls to attempt to achieve the target exploitation rate reference point, which is based on MSY. Harvest control rules are set as strict limits based on stock status and catch limits (Kvamsdal *et al*., 2016). While some fisheries, namely American blue crab and snow crab, used HCRs to constrain fishing mortality, similar rules have been widely used for other fixed-gear fisheries (Zhang *et al*. 2011).

For longstanding crustacean fisheries like lobster and Dungeness crab, success of input controls may have reduced institutional desire for BRP or TAC use in fishery management (Fogarty and Gendron, 2004). Uncertainty from quantifying crustacean growth in $F_{10\%}$ calculations for American lobster led to a BRP that was inconsistent with abundance trends in the fishery (Fogarty and Gendron, 2004). Classifying the American lobster fishery as overfished based on BRP outputs, while population abundance and landings increased, created negative management inertia toward using more comprehensive BRPs as management tools (Fogarty and Gendron, 2004, ASMFC 2020). Adequate biological knowledge is needed to support use of reference points that can meaningfully conserve spawning stock biomass or other population cohorts (Gabriel and Mace, 1999). Difficulty applying reference points, such as fishing mortality linked to spawning potential, is rooted in crustacean biology (Hodgdon *et al*. 2022). Crustacean spawner success influences reference points like $F_{10\%}$, where increased spawner success and highly productive mature spawners allow higher fishing mortality while sustaining recruitment, compared to $F_{40\%}$ that is often used for finfish species (Fogarty and Gendron, 2004, Lynch *et al*. 2018). While an appropriate level of fishing mortality to conserve spawning potential can be challenging to identify, as for American lobster, low reference points require a life history that is resilient to fishery mortality (Fogarty and Gendron, 2004; Smith and Sainte-Marie, 2004).

We found that all case study species had thermal preferences or limits that would likely influence their abundance and distribution in response to climate change. Crustacean stocks are often characterized as emerging, high-value fisheries compared to finfish species with longer fishing histories (Boenish et al. 2021). However, management of crustacean fisheries must account for increasing exploitation and climate-forced environmental changes in what are typically data-limited assessments due to sampling limitations and methodological challenges (Hodgdon *et al*. 2022). For poorly performing stocks, like Gulf of Maine northern shrimp and snow crab, stock declines have been attributed to climatic shifts that dramatically affected recruitment, mortality, and biomass (ASMFC 2018, Szuwalski et al., 2023). Ocean warming has thus far benefitted overall abundance and spatial habitat suitability for some species like American lobster, but fishing communities still rely on these species at the edges of their thermal tolerance (Goldstein *et al*. 2022). The continuous decline of the American lobster fishery in Southern New England, and the total moratorium on harvest of Gulf of Maine northern shrimp, indicate the potential cost to community resilience at equatorial margins of exploited crustacean species. We found that all case study species already experienced distributional shifts or recruitment changes at some scale due to thermal preferences. Input control management is poorly suited to predicting such changes, thereby creating an additional need to develop forecasting stock assessment tools. Applying climate-adaptive management frameworks like BRPs does not produce meaningful stock status improvement with assumed stationarity of population processes (Szuwalski and Hollowed, 2016). Without a comprehensive understanding of crustacean population processes, a status quo approach may yield better conservation results than implementing BRPs (Szuwalski et al. 2022). Since all case study species were responsive to climate forced environmental changes, caution is warranted when applying new BRPs to species historically managed with input controls.

Application of scientifically justifiable management measures like BRPs depends on both scientific interest and organizational frameworks that add positive or negative inertia to exploratory assessments across fisheries science (Eddy *et al*. 2023), although transparency of methodology varies widely across national and agency boundaries. Nearly 70% of crustacean landings are in the northwest Pacific and Indian oceans (Boenish et al. 2021), but little public information exists about aspects of stock assessment and management of these fisheries (Hodgdon et al. 2022). The lack of uniform frameworks hinders application of BRPs to crustaceans that are assessed outside of common management practices. While the U.S. scientific and management community around snow crab has explored applying every BRP we reviewed, the Dungeness crab fishery relies on a traditional landings trend-based approach without non-empirical BRPs. Indonesian crustacean fisheries have explored applications of reference points, Z and $F_{X\%}$, as part of national fisheries research goals despite lacking the long time series of data of U.S. fisheries. The confounding effect of management inertia and framework development can explain part of this difference.

Implementation of complex stock assessment models are restricted by limitations on data, research capacity, and modeling institutional knowledge across agencies (Hodgdon *et al*. 2022). Case study experts did not identify any data streams that were underutilized due to a lack of modeling capacity, but often cited lack of biological data or sufficiently long time series as the largest constraints on modeling complexity for crustacean species. Even in management frameworks that swiftly implemented sampling schemes for novel growing fisheries, not all modeling methodologies yielded satisfactory results with a short time series of data. Case study fisheries with data-limited management measures, like Indonesian BSC, may also experience current or historic limits on research capacity as confounding effects (Ernawati *et al.* 2021).

Fishery management plans (FMP) are useful for describing species biology, fishery behavior, and known management issues. FMPs are useful for setting discrete fishery management goals to provide a framework for regulating fisheries (Die 2009). We found FMPs for all case study fisheries, although some FMPs differed from those described in the Magnuson Stevens Act, which applies to U.S. crustacean fisheries. Ubiquitous use of FMPs for all case studies confirmed that FMPs were useful for identifying management priorities and applying rules in a data-poor environment.

Conclusion

Given the wide array of management techniques that are more feasible for crustaceans than finfish (e.g., greater selectivity possible due to sexual dimorphism), and the unique biology and life history characteristics of crustacea, fisheries management plans must be unique to each fisheries' priorities to achieve management goals. Biologically specific plans are just as necessary for data-rich species as for data-poor species. Life histories of crustacean species limits use of standard finfish assessment models and BRPs, which manifests in systemic reliance on size-structured models and empirical metrics like CPUE and landings.

Case studies reviewed here demonstrated that even crustacean fisheries that are data-rich, well-studied, and well-managed, rarely implemented BRPs in management plans even if BRPs were developed for the fishery. Case study species we reviewed generally continued to support robust fisheries despite large differences in management strategies and data availability. While BRPs may seem less useful for comprehensively managed fisheries with long-term data and well-established protocols managing around variation in landings, BRP metrics are also easiest to apply to such fisheries. In contrast, emerging fisheries with short or nonexistent time-series of data and poorly described fishery behavior have the most potential to gain from integrating BRPs into fishery management plans because the unique biology and life history of each species requires species-specific data and information, although a lack of detailed biological information is the greatest obstacle to implementation.

Due to the obstacles surrounding BRP development and implementation for a crustacean fishery, a species-specific approach towards reference point use is needed, rather than broad recommendations that could be applicable towards all crustacean fisheries. Although data collection and capacity face many barriers in emerging fisheries, BRP development and implementation in data-limited fisheries are useful for creating FMPs for regulations and rules that establish management priorities of the fishery. In data-rich fisheries, or fisheries that have already developed BRP metrics, BRPs must still be developed and incorporated into the FMP to diversify the management protocol and act as another standard for comparison to management objectives. Creation and inclusion of BRPs does not take away from management practices that may already exist and be considered adequate, but instead act to enhance the FMP by acting as another way to assess progress towards management objectives.

While robust stock assessment should be a goal for all crustacean fisheries, we found a pattern of successful management being supported by a hybrid of input and output control use. Crustacean exceptionalism is not our main conclusion, because variability in the biology and ecology of finfish species is similar to crustaceans. However, adapting traditional modeling methods to account for stepwise growth and a lack of age-estimation methods for crustacean species make data-limited crustacean management quantitatively challenging. While BRPs are important for comprehensive management of marine fisheries, input controls can be used successfully as a safeguard while describing population dynamics and developing appropriate management strategies for these fisheries. Success of input controls in management is especially applicable to fisheries management hindered by a lack of stock assessment scientists, imperfect local understanding of assessment models, or data-wise penurious management programs. Output controls have also performed well in crustacean fishery management, compounding biological factors like crustacean paternal care to enhance recruitment.

As crustacean fisheries continue growing globally and landings continue increasing, active management is needed for long-term sustainability of crustacean fisheries. Integration of BRPs as a component of the overall management strategy is beneficial to both emerging and historically profitable fisheries, however care must be taken to account for non-stationarity in life history processes. For fisheries with existing management objectives, complex theory based BRPs should be implemented to assess progress toward goals. For emerging fisheries, empirical BRPs can be used in fisheries management plans as *de facto* management objectives or regulations. Traditional empirical reference points and technical input and output controls can be used to sustainably manage a fishery if biologically appropriate safeguards are used, especially compared to historic finfish stocks that used a similar approach. Management agencies must consider how historically successful application of input controls may impact innovative inertia and application of model-derived reference points, especially in the face of climactically driven stock shifts.

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Works Cited:

Apostolaki, P., and Hillary, R. 2009. Harvest control rules in the context of fishery-independent management of fish stocks. Aquat. Living Resour. **22**(2): 217–224. doi:10.1051/alr/2009022.

Assessment, I. E. (2017). Yield, Threshold Number of Permits, and Transit Provisions.

Atlantic States Marine Fisheries Commission. 2004. Assessment Report for Gulf of Maine Northern Shrimp.

Atlantic States Marine Fisheries Commission. 2018. Assessment Report for Gulf of Maine Northern Shrimp.

Atlantic States Marine Fisheries Commission. 2020. American Lobster Benchmark Stock Assessment.

Atlantic States Marine Fisheries Commission. 2021. Annual Report.

Azra MN, Chen J-C, Ikhwanuddin M, Abol-Munafi AB. 2018. Thermal tolerance and locomotor activity of blue swimmer crab Portunus pelagicus instar reared at different temperatures. Journal of Thermal Biology.;74:234-240.

Baeza, J. A., Simpson, L., Ambrosio, L. J., Mora, N., Guéron, R., & Childress, M. J. 2016. Active parental care, reproductive performance, and a novel egg predator affecting reproductive investment in the Caribbean spiny lobster Panulirus argus. *BMC Zoology*, *1*(1), 1-15.

Behan, J., Li, B., and Chen, Y. 2021. Examining Scale Dependent Environmental Effects on American Lobster (Homarus americanus) Spatial Distribution in a Changing Gulf of Maine. Front. Mar. Sci. **8**(July). doi:10.3389/fmars.2021.680541.

Bellido, J. M., Sumaila, U. R., Sánchez-Lizaso, J. L., Palomares, M. L., & Pauly, D. 2020. Input versus output controls as instruments for fisheries management with a focus on Mediterranean fisheries. Marine Policy, 118, 103786.

Bergstrom, B. 2000. The Biology of Pandalus. Adv. Mar. Biol. 38. 10.1016/S0065-2881(00)38003-8.

Boenish, R., Kritzer, J.P., Kleisner, K., Steneck, R.S., Werner, K.M., Zhu, W., Schram, F., Rader, D., Cheung, W., Ingles, J., Tian, Y., and Mimikakis, J. 2021. The global rise of crustacean fisheries. Front. Ecol. Environ. **20**(2): 102–110. doi:10.1002/fee.2431.

Botsford, L.W. 2001. Physical influences on recruitment to California Current invertebrate populations on multiple scales. ICES J. Mar. Sci. 58:1081-1091

Bromilow, M. 2021. Chesapeake Bay Blue Crab Advisory Report. CBSAC Meeting Date: May 18, 2021. Final Report: June 22, 2021.

Burmeister, A., and Rigét, F. Serial No. 7238 NAFO SCR Doc. 21/040 NAFO/ICES PANDALUS ASSESSMENT GROUP—1–5 November 2021.

Burmeister, A. and Riget, F. 2018. The Fishery for Northern Shrimp (Pandalus borealis) off West Greenland, 1970–2018. NAFO SCR Doc. 18/057, Ser. No. 6871. 44 pp.

Caddy, J.F., and Mahon, R. 1995. Reference Points for Fisheries Management: FAO Technical Paper 347: 83.

Caddy, J.F. 2004. Current usage of fisheries indicators and reference points, and their potential application to management of fisheries for marine invertebrates. Can. J. Fish. Aquat. Sci. **61**(8): 1307–1324. doi:10.1139/F04-132.

Caputi, N., Chandrapavan, A., Kangas, M., de Lestang, S., Hart, A., Johnston, D., and Penn, J. 2021. Stock-recruitment-environment relationships of invertebrate resources in Western Australia and their link to pro-active management harvest strategies. Mar. Policy **133**(December 2020): 104728. Elsevier Ltd. doi:10.1016/j.marpol.2021.104728.

Caputi, N., Lestang, S., de, Frusher, S. and Wahle, R.A. 2013. The Impact of Climate Change on Exploited Lobster Stocks. In Lobsters: Biology, Management, Aquaculture and Fisheries, B.F. Phillips (Ed.).

Carver, A. M., Wolcott, T. G., Wolcott, D. L., & Hines, A. H. 2005. Unnatural selection: effects of a male-focused size-selective fishery on reproductive potential of a blue crab population. Journal of Experimental Marine Biology and Ecology, 319(1-2), 29-41.

Chang, Y.J., Chi-Lu, S., Chen, Y., Su-Zan, Y. 2012. Modelling the growth of crustacean species. Reviews in Fish Biology and Fisheries. 22. 157-187.

Chen, Y., and Wilson, C. 2002. A simulation study to evaluate impacts of uncertainty on the assessment of the American lobster fishery in the Gulf of Maine. Can. J. Fish. Aquat. Sci. **59**(8): 1394–1403. doi:10.1139/f02-102.

Chesapeake Bay Stock Assessment Committee (CBSAC). 2018. Chesapeake Bay Blue Crab Advisory Report.

Chesapeake Bay Stock Assessment Committee (CBSAC). 2021. Chesapeake Bay Blue Crab Advisory Report.

Clark, W.G. 1993. The effect of recruitment variability on the choice of a target level of spawning biomass per recruit. In Kruse, G., Eggers, D.M., Marasco, R.J., Pautzke, C. and Quinn II, T.F.,eds. Proc. Int. Symp. Management Strategies for Exploited Fish Populations. Fairbanks, AK: U.of Alaska Sea Grant College Program Rep.

Clark, S. H., Cadrin, S. X., Schick, D. F., Diodati, P. J., Armstrong, M. P., & McCarron, D. (2000). The Gulf of Maine northern shrimp (Pandalus borealis) fishery: a review of the record. Journal of Northwest Atlantic Fishery Science, 27, 193-226.

Clarke, S. and Hoyle, S., 2014. Development of limit reference points for elasmobranchs. Proceedings of the Scientific Committee Tenth Regular Session, Majuro, Marshall Islands, pp.6-14.

Collie, J.S., and Gislason, H. 2001. Biological reference points for fish stocks in a multispecies context. Can. J. Fish. Aquat. Sci. **58**(11): 2167–2176. doi:10.1139/cjfas-58-11-2167.

Cook, H. L., & Lindner, M. J. (1970). Synopsis of biological data on the brown shrimp, Penaeus aztecus Ives, 1891.

Dickinson G. H., Rittschoff D., and Latanich C.. 2006. Spawning biology of the blue crab, *Callinectes sapidus*, in North Carolina. *Bulletin of Marine Science* 79: 273-285.

Die, D.J. 2009. Fisheries Management Plans. In A Fishery Manager's Guidebook (eds K.L. Cochrane and S.M. Garcia).

Divine, L.M., Mueter, F.J., Kruse, G.H., Bluhm, B.A., Jewett, S.C., and Iken, K. 2019. New estimates of weight-at-size, maturity-at-size, fecundity, and biomass of snow crab, Chionoecetes opilio, in the Arctic Ocean off Alaska. Fish. Res. **218**(May): 246–258. Elsevier. doi:10.1016/j.fishres.2019.05.002.

Eddy, T., Duplisea, D., Robertson, M., Ruiz-Díaz, R., Solberg, C.A., and Zhang, F. 2023. Barriers to implementation of dynamic reference points in fisheries management. FACETS. 8(): 1-10.

Ernawati, T., Sumiono, B., and Maddupa, H., 2017. Reproductive ecology, spawning potential, and breeding season of blue swimming crab (Portunidae: Portunus pelagicus) in Java Sea, Indonesia. Biodiversitas 18(4), 1705–1713. doi: 10.13057/biodiv/d180451.

Ernawati, T., Priatna, A., and Satria, F. 2019. Biological reference points of painted spiny lobster Panulirus versicolor (Latreille, 1804) in Karimunjawa waters, Indonesia. Indonesian Fisheries Research Journal, 25(2).

Ernawati, T., Budiarti, T.W., Yuniarta, S., 2021. Fisheries management for the Blue Swimmer Crab (*Portunus pelagicus*) in the Java Sea, Indonesia. In: Loneragan, N.R., Wiryawan, B., Hordyk, A.R., Halim, A., Proctor, C., Satria, F., Yulianto, I. (Eds), Proceedings from Workshops on Management Strategy Evaluation of Data-Limited Fisheries: Towards Sustainability – Applying the Method Evaluation and Risk Assessment Tool to Seven Indonesian Fisheries. Murdoch University, Western Australia, and IPB University, Indonesia [ISBN 978-0-646-82951-7], pp. 29–49.

FAO. 1997. FAO Technical Guidelines for Responsible Fisheries - Fisheries Management - 4 ISBN 92-5-103962-3.

FAO. 2021. FAO Yearbook. Fishery and Aquaculture Statistics 2019. Available at: https://www.fao.org/fishery/en/publications/287024

FAO, Global Capture Production Database License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/fishery/statistics-query/en/capture. Data of Access: 30/11/2022.

Fogarty, M.J., and Gendron, L. 2004. Biological reference points for American lobster (Homarus americanus) populations: Limits to exploitation and the precautionary approach. Can. J. Fish. Aquat. Sci. **61**(8): 1392–1403. doi:10.1139/F04-140.

Four Alternative Conservation and Management Measures." National Research Council. 1999. Sharing the Fish: Toward a National Policy on Individual Fishing Quotas. Washington, DC: The National Academies Press. doi: 10.17226/6335.

Fox, C. J., Albalat, A., Valentinsson, D., Nilsson, H. C., Armstrong, F., Randall, P., & Catchpole, T. (2020). Survival rates for Nephrops norvegicus discarded from Northern European trawl fisheries. *ICES Journal of Marine Science*, *77*(5), 1698-1710.

Gabriel, W.L., and Mace, P.M. 1999. A review of biological reference points in the context of the precautionary approach. Proc. fifth Natl. NMFS Stock Assess. Work. Provid. Sci. advice to implement precautionary approach under Magnuson-Stevens Fish. Conserv. Manag. act. NOAA Tech Memo NMFS-F/SPO-40 (1934): 34–45.

Garber-Yonts, B. E., & Lee, J. (2020). Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands Area: Economic Status of the BSAI King and Tanner Crab Fisheries off Alaska, 2019.

Goldstein, J., Zarrella-Smith, K., Pugh, T. 2022. Recent declines in American lobster fecundity in southern New England: drivers and implications, ICES Journal of Marine Science, Volume 79, Issue 5, Pages 1662–1674

Greenland (GRL) exports, imports, and trade partners (no date) *OEC*. Available at: https://oec.world/en/profile/country/grl?yearSelector1=2020 (Accessed: 02 June 2023).

Haynes, E.B., and R.L. Wigley. 1969. Biology of the northern shrimp, *Pandalus borealis*, in the Gulf of Maine. *Trans. Am. Fish. Soc.*, **98**(1): 60-76

Hodgdon, C. T., Khalsa, N. S., Li, Y., Sun, M., Boenish, R., & Chen, Y. 2022. Global crustacean stock assessment modelling: Reconciling available data and complexity. Fish and Fisheries, 23(3), 697-707.

Hodgdon, C.T., Mazur, M.D., Friedland, K.D., Willse, N., and Chen, Y. 2021. Consequences of model assumptions when projecting habitat suitability: a caution of forecasting under uncertainties. ICES J. Mar. Sci. **78**(6): 2092–2108. doi:10.1093/icesjms/fsab101.

Huang, P., Woodward, R.T., Wilberg, M.J., and Tomberlin, D. 2015. Management Evaluation for the Chesapeake Bay Blue Crab Fishery: An Integrated Bioeconomic Approach. North Am. J. Fish. Manag. **35**(2): 216–228. doi:10.1080/02755947.2014.986342.

ICES. 2022. Joint NAFO\ICES Pandalus Assessment Working Group (NIPAG). ICES Scientific Reports. 4:38. 25 pp.

Jensen, G. C., and Armstrong, D. A. 1987. Range extensions of some northeastern Pacific Decapoda. *Crustaceana*, *52*(2), 215-217.

Kangas, M. 2000. Synopsis of the biology and exploitation of the blue swimmer crab, Portunus pelagicus Linnaeus, in Western Australia. Fish. Res. Rep. Fish. West Aus.. 121.

Kembaren, D.D., Anggawangsa, R.F., Hargiyatno, I.T., Hakim, A.A., Ekawaty, R., Jafani, A.S., 2021. Fisheries management for the Scalloped Spiny Lobster (*Panulirus homarus*) in the waters of southern Yogyakarta and Pacitan, Indonesia. In: Loneragan, N.R., Wiryawan, B., Hordyk, A.R., Halim, A., Proctor, C., Satria, F., Yulianto, I. (Eds), *Proceedings from Workshops on Management Strategy Evaluation of Data-Limited Fisheries: Towards Sustainability – Applying the Method Evaluation and Risk Assessment Tool to Seven Indonesian Fisheries.* Murdoch University, Western Australia, and IPB University, Bogor, Indonesia [ISBN 978-0-646-82951-7], pp. 51–63

Kembaren, D.D., and Suman, A. 2023. Inferring Stock Status of Painted Spiny Lobster (Panulirus versicolor) in Aru Islands Waters, Indonesia. Turkish Journal of Fisheries and Aquatic Sciences, 23(SI), TRJFAS21543. https://doi.org/10.4194/TRJFAS21543

Kennedy, V.S., L. Bolognini, J. Dulčić, R.J. Woodland, M.J. Wilberg, and L. A. Harris. 2021. Fisheries of the Adriatic Sea and the Chesapeake Bay. P. 203-227 In T. Malone, A. Malej, and J. Faganeli eds. Vectors of Change in Coastal Ecosystems and the Services They Provide: A Comparative Analysis of the Northern Adriatic Sea and Chesapeake Bay. AGU-Wiley.

Kvamsdal, S. F., Eide, A., Ekerhovd, N. A., Enberg, K., Gudmundsdottir, A., Hoel, A. H., & Vestergaard, N. (2016). Harvest control rules in modern fisheries management. Harvest control rules in modern fisheries management. Elementa: Science of the Anthropocene, 4.

Lassuy, D R. 1983. "Species profiles - life histories and environmental requirements (Gulf of Mexico): brown shrimp". United States.

Lynch, P., Methot, R., & Link, J, 2018. Implementing a Next Generation Stock Assessment Enterprise. An Update to the NOAA Fisheries Stock Assessment Improvement Plan. 10.7755/TMSPO.183.

McTigue, T. A., & Zimmerman, R. J. (1991). Carnivory vs. herbivory in juvenile Penaeus setiferus (Linnaeus) and Penaeus aztecus (Ives). Journal of Experimental Marine Biology and Ecology, 151(1), 1-16.

McTigue, T. A., & Zimmerman, R. J. (1998). The use of infauna by juvenile Penaeus aztecus Ives and Penaeus setiferus (Linnaeus). Estuaries, 21, 160-175.

Methot Jr, R. D., and Botsford, L. W. (1982). Estimated preseason abundance in the California Dungeness crab (Cancer magister) fisheries. Canadian Journal of Fisheries and Aquatic Sciences, 39(8), 1077-1083.

Methot, R.D. 2009. Stock assessment: operational models in support of fisheries management. In Beamish and Rothschild (ed) Future of Fishery Science. Proceedings of the 50th Anniversary Symposium of the American Institute of Fishery Research Biologists, Seattle, WA. Springer. Fish and Fisheries Series, Vol. 31: Pg. 137-165.

Miller, T., Willberg, M., Colton, A., Davis, G., Sharov, A., Lipcius, R.N., Ralph, G., Johnson, E., and Kaufman, A. 2011. Stock assessment of the Blue Crab in Chesapeake Bay. Tech. Rep. Ser. Univ. Maryl. Cent. Environ. Sci.: 214. Available from http://hjort.cbl.umces.edu/crabs/docs/Assessment_document_final_approved.pdf%0Ahttp://hjort.cbl.umces.edu/crabs/docs/Assessment_document_final_approved.pdf.

Morison, A. K. 2004. Input and output controls in fisheries management: a plea for more consistency in terminology. Fisheries Management and Ecology, 11(6), 411-413.

NAFO/ICES Pandalus Assessment Group (NIPAG). 2019. Assessment Group Meeting November 2019. Available at: https://www.nafo.int/Portals/0/PDFs/sc/2019/scs19-24.pdf

National Academies of Sciences, Engineering, and Medicine. 1999. Sharing the Fish: Toward a National Policy on Individual Fishing Quotas. Washington, DC: The National Academies Press.

National Oceanographic and Atmospheric Administration (NOAA) Commercial Fisheries Landings Database. 2023. Available at: https://www.fisheries.noaa.gov

OECD, 2022, OECD Review of Fisheries 2022, OECD Publishing

Otto, R.S. 1998. Assessment of the eastern Bering Sea snow crab, Chionoecetes opilio, stock under the terminal molting hypothesis. In Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management. Can. Spec. Publ. Fish. Aquat. Sci. 125.pp. 109-124.

Ozawa, H. 2013. The history of sexual dimorphism in Ostracoda (Arthropoda, Crustacea) since the Palaeozoic. Sexual dimorphism. InTech, Rijeka, Croatia, 51-80.

Pacific States Marine Fisheries Commission (PSMFC). 2014. Dungeness Crab Report. Available at: https://www.psmfc.org/crab/2014-2015%20files/DUNGENESS%20CRAB%20REPORT2014.pdf

Penn, James. 1984. The behaviour and catchability of some commercially exploited penaeids and their relationship to stock and recruitment. Penaeid Shrimps —Their Biology and Management. 173-186.

Penn, J., Caputi, N., De Lestang, S., Johnston, D., Kangas, M., and Bopp, J. 2018. Crustacean Fisheries.

Phillips BF, Booth JD, Cobb JS, Jeffs AG, McWilliam P. 2006. Larval and Postlarval Ecology (Chapter 7). In: Phillips BF (Ed.) Lobsters: Biology, Management, Aquaculture and Fisheries. Blackwell Publishing: 231-262

Pope, J. 2009. Input and Output Controls: The Practice of Fishing Effort and Catch Management in Responsible Fisheries.

Punt, A. E. (2010). Harvest control rules and fisheries management. Handbook of marine fisheries conservation and management, 582-594.

Punt, A.E., Campbell, R.A. and Smith, A.D., 2001. Evaluating empirical indicators and reference points for fisheries management: application to the broadbill swordfish fishery off eastern Australia. Marine and freshwater research, 52(6), pp.819-832.

Punt, A.E., Huang, T.C., and Maunder, M.N. 2013. Review of integrated size-structured models for stock assessment of hard-to-age crustacean and mollusc species, ICES J. Mar. Sci, Volume 70, Issue 1, Pages 16–33,

Rains, S.A.M., Wilberg, M.J., and Miller, T.J. 2018. Evaluation of fishery-induced sperm limitation in Chesapeake Bay blue crab using an individual-based model. Mar. Ecol. Prog. Ser. **596**: 127–142. doi:10.3354/meps12595.

Rasmuson, L.K. 2013. The biology, ecology and fishery of the Dungeness crab, cancer magister. *In* Advances in Marine Biology, 1st edition. Elsevier Ltd. doi:10.1016/B978-0-12-410498-3.00003-3.

Restrepo, V. R. (1998). Technical guidance on the use of precautionary approaches to implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act. NOAA Tech. Memo.

Richerson, K., Punt, A. E., and Holland, D. S. 2020. Nearly a half century of high but sustainable exploitation in the Dungeness crab (Cancer magister) fishery. Fisheries Research, 226, 105528.

Rodrigues, E., Bell, M., & Mesquita, C. 2015. Discard survival and condition in Orkney brown crabs (Cancer pagurus). Fishing Industry Science Alliance (FISA), 648-665.

Rugolo, L., Pengilly, D., MacIntosh, R., Gravel, K., 2005. Reproductive Dynamics and Life History of Snow Crab In the Eastern Bering Sea. Bering Sea Snow Crab Fishery Restoration Research: Final Comprehensive Performance Report. NOAA Cooperative Agreement NA17FW1274., Div. Commer. Fish. Alaska Dep. Fish Game, Juneau, AK (2005), pp. 57-323

Sharov, A.F., Vølstad, J.H., Davis, G.R., Davis, B.K., Lipcius, R.N., and Montane, M.M. 2003. Abundance and exploitation rate of the blue crab (Callinectes sapidus) in Chesapeake Bay. Bull. Mar. Sci. **72**(2): 543–565.

Siddeek, M. S. M. 2003. Determination of biological reference points for Bristol Bay red king crab. Fisheries Research, 65(1–3), 427–451. https://doi.org/10.1016/j.fishres.2003.09.030

Smith, M.T., and Addison, J.T. 2003. Methods for stock assessment of crustacean fisheries. Fish. Res. **65**(1–3): 231–256. doi:10.1016/j.fishres.2003.09.017.

Smith, S. and Sainte-Marie, B. 2004. Biological reference points for invertebrate fisheries: Introduction. Can. J. Fish. Aquat. Sci. 61. 1303-1306. 10.1139/f04-135.

Steneck, R.S., and Wilson, C.J. 2001. Large-scale and long-term, spatial and temporal patterns in demography and landings of the American lobster, Homarus americanus , in Maine. Mar. Freshw. Res. **52**.

Stevens, B.G. 2021. The ups and downs of traps: Environmental impacts, entanglement, mitigation, and the future of trap fishing for crustaceans and fish. ICES J. Mar. Sci. **78**(2): 584–596. doi:10.1093/icesjms/fsaa135.

Szuwalski, C.S., Hollowed, A.B. 2016 Climate change and non-stationary population processes in fisheries management. ICES Journal of Marine Science. Volume 73, Issue 5, May/June 2016, Pages 1297–1305.

Szuwalski, C.S., Hollowed, A.B., Holsman, K.K., Ianelli, J.N., Legault, C.M., Melnychuk, M.C., Ovando, D., & Punt, A.E. 2023. Unintended consequences of climate-adaptive fisheries management targets. Fish and Fisheries, 24, 439–453.

Szuwalski, C.S., Aydin, K., Fedewa, E.J., Garber-Yonts, B., Litzow, M.A. 2023. The collapse of eastern Bering Sea snow crab. Science. 382(6668): 306-310.

Thiel, M. A. R. T. I. N. 2003. Extended parental care in crustaceans–an update. *Revista Chilena de Historia Natural*, *76*(2), 205-218.

Tirtadanu, Suman, A., Chodrijah, U., Kang, B., and Zhang, C. I. 2021. Stock assessment and management implications of three lobster species in Gunungkidul waters, Indonesia. *Ocean and Coastal Management*, *211*. https://doi.org/10.1016/j.ocecoaman.2021.105780

Urban, D.J. 2015. Discard mortality rates in the Bering Sea snow crab, Chionoecetes opilio, fishery J. ICES J. Mar. Sci. **72**(5): 1525–1529. doi:10.1038/278097a0.

Wieland K., Siegstad H. 2012 Environmental factors affecting recruitment of northern shrimp Pandalus borealis in West Greenland waters. Mar Ecol Prog Ser 469:297-306.

Williams, E.H., and Shertzer, K.W. 2003. Implications of life-history invariants for biological reference points used in fishery management. Can. J. Fish. Aquat. Sci. **60**(6): 710–720. doi:10.1139/F03-059.

Zairion, Wardiatno, Y., and Fahrudin, A., 2015. Sexual maturity, reproductive pattern and spawning female population of the blue swimming crab Portunus pelagicus (Brachyura: Portunidae) in East Lampung coastal waters, Indonesia. Indian Journal of Science and Technology 8(7), 596–607.

Zhang, Y., Chen, Y., and Wilson, C. 2011. Developing and evaluating harvest control rules with different biological reference points for the American lobster (Homarus americanus) fishery in the Gulf of Maine. ICES J. Mar. Sci. **68**(7): 1511–1524. doi:10.1093/icesjms/fsr071.

Ziegler, F., Hornborg, S., Valentinsson, D., Skontorp Hognes, E., Søvik, G., & Ritzau Eigaard, O. 2016. Same stock, different management: quantifying the sustainability of three shrimp fisheries in the Skagerrak from a product perspective. ICES Journal of Marine Science, 73(7), 1806-1814.

Zimmerman, R. J., Minello, T. J., & Rozas, L. P. (2000). Salt marsh linkages to productivity of penaeid shrimps and blue crabs in the northern Gulf of Mexico. Concepts and controversies in tidal marsh ecology, 293-314.

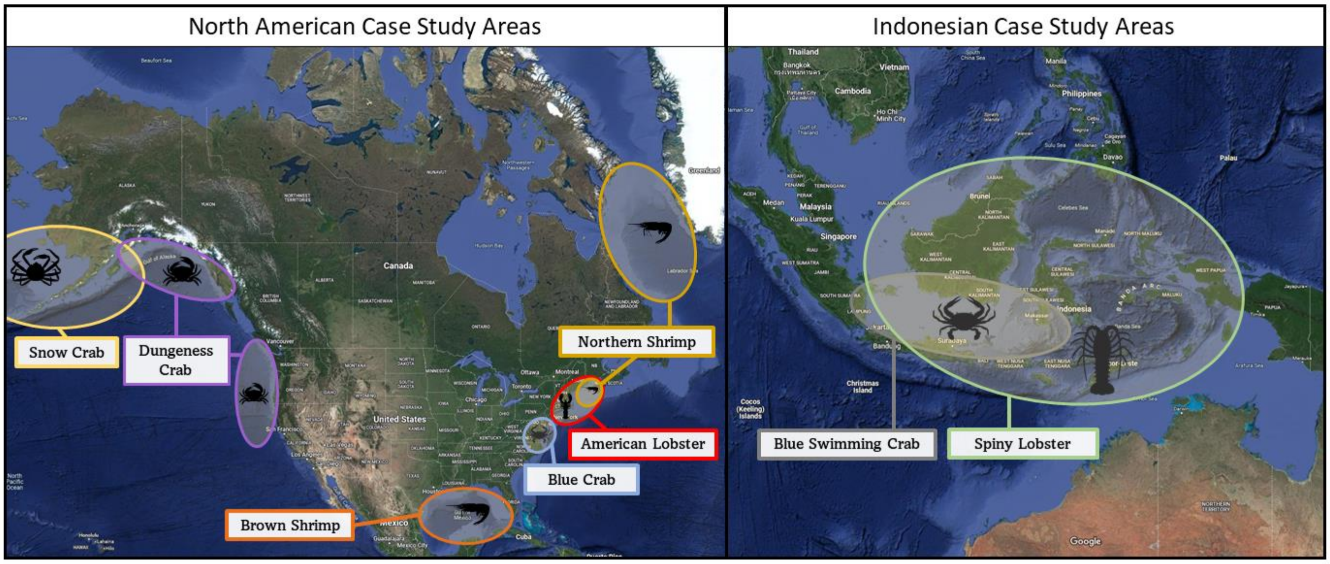


Figure 1: Locations of crustacean fishery case studies reviewed, including the country and approximate area where most of the fishery operated under the purview of case study experts (Map data Google 2023).

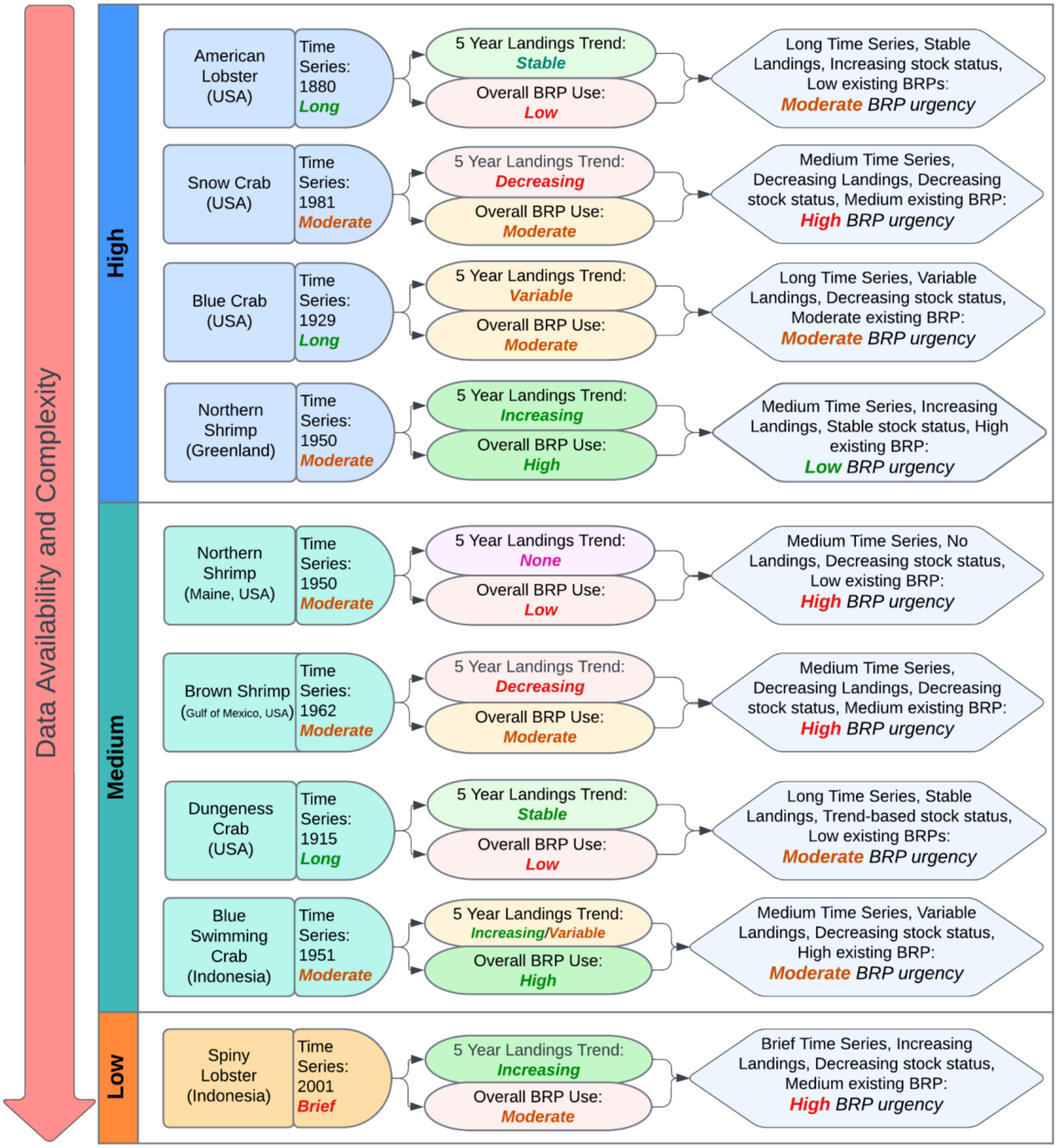
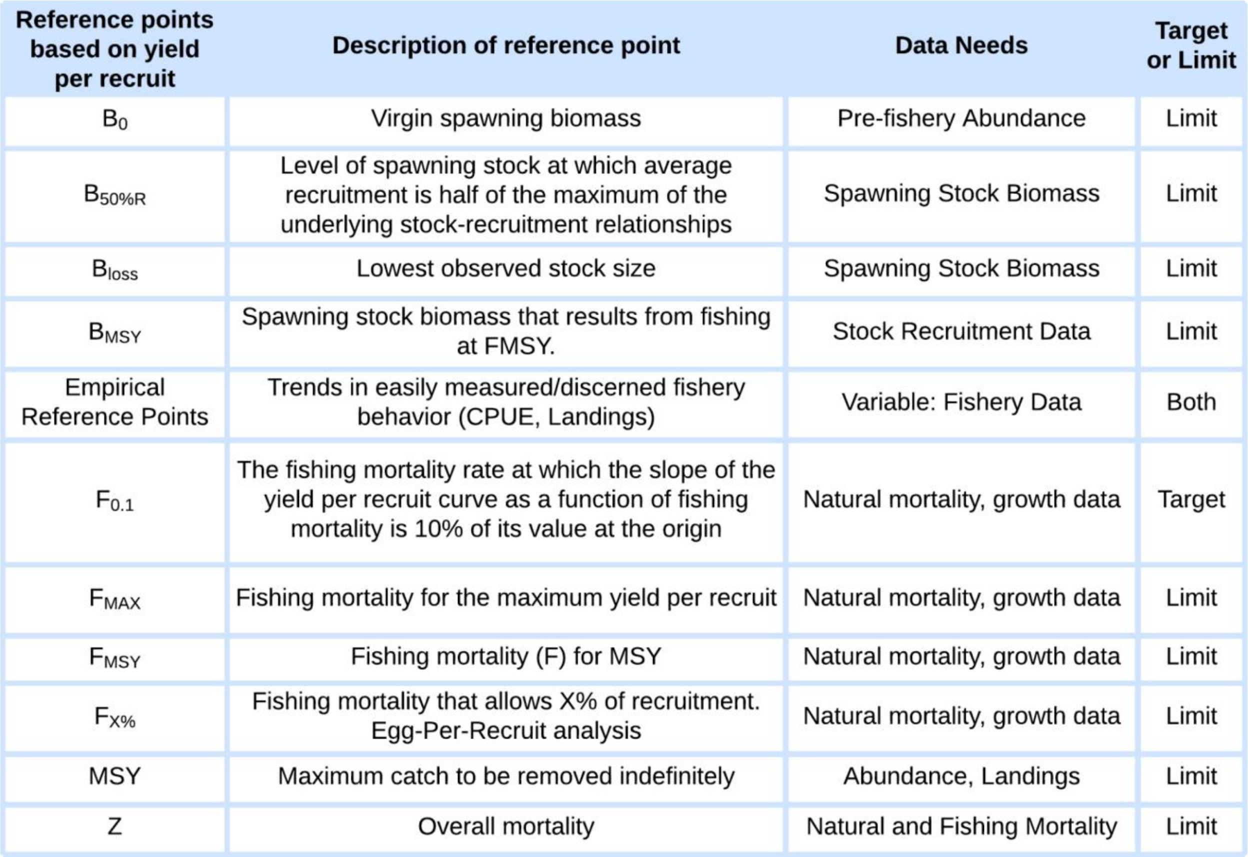


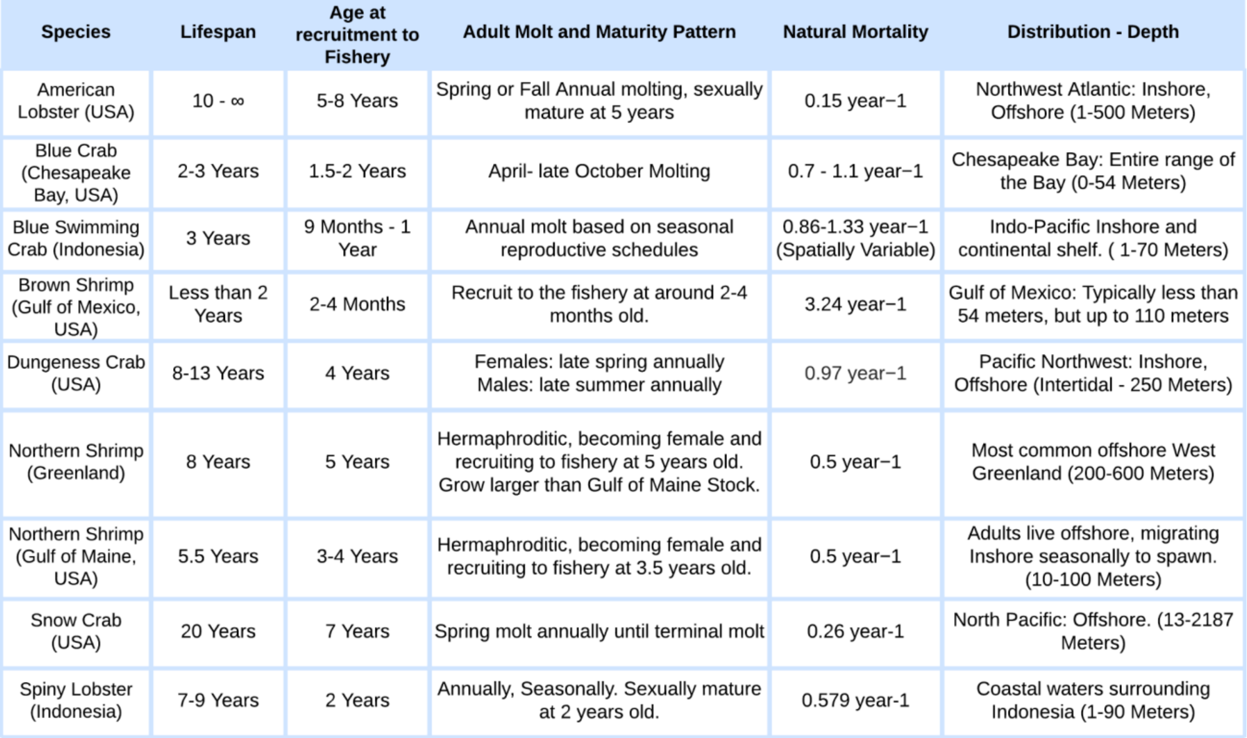
Figure 2: Characterizations of nine crustacean fishery case studies, including length of the landings time series, 5-year trend in landings, and number of applied reference points in relation to data availability and complexity (see Figure 1 for location specificity). Case studies are organized across a high-medium-low scale of data availability (inclusive of time series length and biological data complexity).

Table 1: Biological reference point definitions, data needed, and target or limit harvest control rules commonly used in finfish fisheries management plans (see Figure 1 for location specificity)..



Reference points based on yield per recruit	Description of reference point	Data Needs	Target or Limit
B_0	Virgin spawning biomass	Pre-fishery Abundance	Limit
$B_{50\%R}$	Level of spawning stock at which average recruitment is half of the maximum of the underlying stock-recruitment relationships	Spawning Stock Biomass	Limit
B_{loss}	Lowest observed stock size	Spawning Stock Biomass	Limit
B_{MSY}	Spawning stock biomass that results from fishing at FMSY.	Stock Recruitment Data	Limit
Empirical Reference Points	Trends in easily measured/discerned fishery behavior (CPUE, Landings)	Variable: Fishery Data	Both
$F_{0.1}$	The fishing mortality rate at which the slope of the yield per recruit curve as a function of fishing mortality is 10% of its value at the origin	Natural mortality, growth data	Target
F_{MAX}	Fishing mortality for the maximum yield per recruit	Natural mortality, growth data	Limit
F_{MSY}	Fishing mortality (F) for MSY	Natural mortality, growth data	Limit
$F_{X\%}$	Fishing mortality that allows X% of recruitment. Egg-Per-Recruit analysis	Natural mortality, growth data	Limit
MSY	Maximum catch to be removed indefinitely	Abundance, Landings	Limit
Z	Overall mortality	Natural and Fishing Mortality	Limit

Table 2: Lifespan, age of fishery recruitment, adult molting season, maturity pattern, natural mortality, and global distribution for nine crustacean species case studies (see Figure 1 for location specificity).

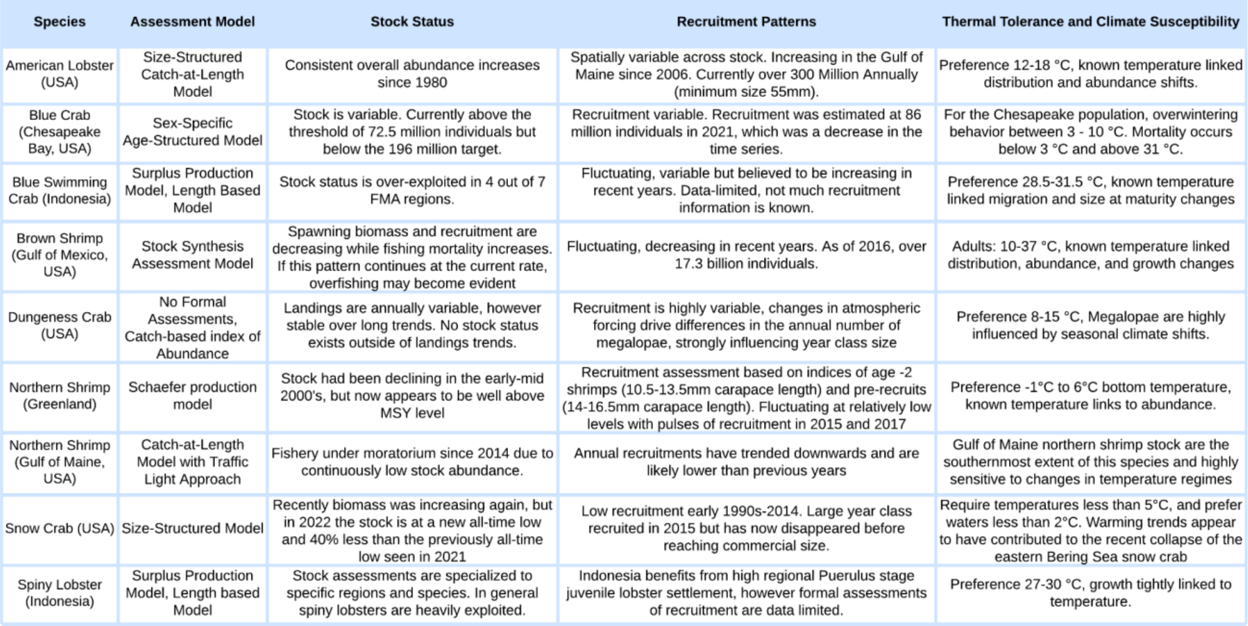


Species	Lifespan	Age at recruitment to Fishery	Adult Molt and Maturity Pattern	Natural Mortality	Distribution - Depth
American Lobster (USA)	10 - ∞	5-8 Years	Spring or Fall Annual molting, sexually mature at 5 years	0.15 year−1	Northwest Atlantic: Inshore, Offshore (1-500 Meters)
Blue Crab (Chesapeake Bay, USA)	2-3 Years	1.5-2 Years	April- late October Molting	0.7 - 1.1 year−1	Chesapeake Bay: Entire range of the Bay (0-54 Meters)
Blue Swimming Crab (Indonesia)	3 Years	9 Months - 1 Year	Annual molt based on seasonal reproductive schedules	0.86-1.33 year−1 (Spatially Variable)	Indo-Pacific Inshore and continental shelf. (1-70 Meters)
Brown Shrimp (Gulf of Mexico, USA)	Less than 2 Years	2-4 Months	Recruit to the fishery at around 2-4 months old.	3.24 year−1	Gulf of Mexico: Typically less than 54 meters, but up to 110 meters
Dungeness Crab (USA)	8-13 Years	4 Years	Females: late spring annually Males: late summer annually	0.97 year−1	Pacific Northwest: Inshore, Offshore (Intertidal - 250 Meters)
Northern Shrimp (Greenland)	8 Years	5 Years	Hermaphroditic, becoming female and recruiting to fishery at 5 years old. Grow larger than Gulf of Maine Stock.	0.5 year−1	Most common offshore West Greenland (200-600 Meters)
Northern Shrimp (Gulf of Maine, USA)	5.5 Years	3-4 Years	Hermaphroditic, becoming female and recruiting to fishery at 3.5 years old.	0.5 year−1	Adults live offshore, migrating Inshore seasonally to spawn. (10-100 Meters)
Snow Crab (USA)	20 Years	7 Years	Spring molt annually until terminal molt	0.26 year-1	North Pacific: Offshore. (13-2187 Meters)
Spiny Lobster (Indonesia)	7-9 Years	2 Years	Annually, Seasonally. Sexually mature at 2 years old.	0.579 year-1	Coastal waters surrounding Indonesia (1-90 Meters)

Table 3: Landings and approximate value, input or output management controls, and fishing method for nine case study Crustacean fisheries (see Figure 1 for locations; value calculated from total landings and a per kilo value provided by case study experts, referenced against known export values).

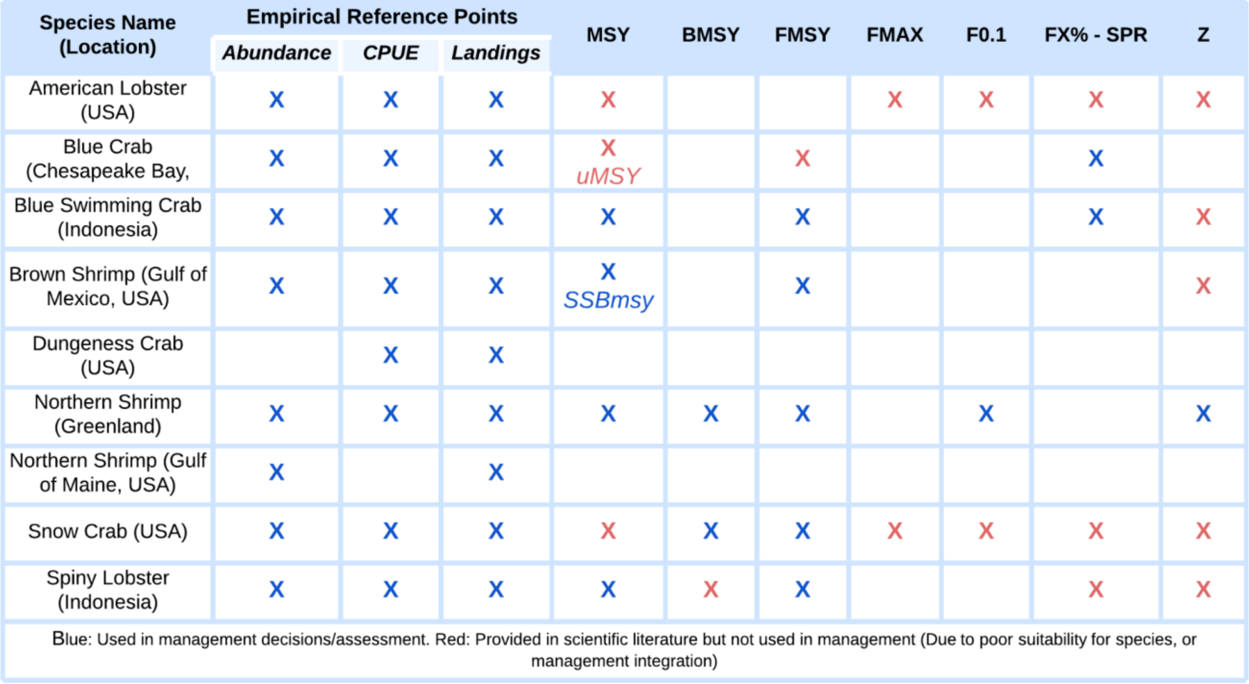
Species	**Landings (Tonnes, 2020)**	**Dollar Value, USD (2020)**	**Management Controls**	**Fishing method**
American Lobster (USA)	54855	530,258,992	Output Control: Size Limits, Female Protections. Input Control: Licenses, Trap Limits	Pot
Blue Crab (Chesapeake Bay, USA)	17025	203,898,327	Output Control: Size Limits, Female Protections Input Control: Gear Limits, Season Limits	Pot, Gillnet, Trotline
Blue Swimming Crab (Indonesia)	92000	460,000,000 (Approximate)	Output Control: Size Limits, Female Protections,	Pots, Gillnet
Brown Shrimp	30391	5,941,778	Input Control: Freeze on new Permits, Seasonal Closures	Trawl
Dungeness Crab (USA)	26485	200,406,780	Output Control: Size Limits, Female Protections Input Control: Season and Trap Limits	Pot
Northern Shrimp (Greenland)	110817	693,000,000 (Approximate)	Output Control: TAC	Trawl
Northern Shrimp (Gulf of Maine, USA)	Fishery Moratorium	-	Fishery Moratorium	-
Snow Crab (USA)	16601	132,287,850	Output Control: TAC, Size Limits, Female Protections Input Control: Size Limits, Female Protections	Pot
Spiny Lobster (Indonesia)	9942	Value cannot be disassociated with larval export for aquaculture	Output Control: Size limits, Female Protections	Gillnet, Hoop Net

Table 4: Stock assessment model, stock status, recruitment pattern, thermal tolerance, and susceptibility to climate change for nine case study Crustacean species (see Figure 1 for location specificity; information provided by case study experts and available scientific literature).



Species	Assessment Model	Stock Status	Recruitment Patterns	Thermal Tolerance and Climate Susceptibility
American Lobster (USA)	Size-Structured Catch-at-Length Model	Consistent overall abundance increases since 1980	Spatially variable across stock. Increasing in the Gulf of Maine since 2006. Currently over 300 Million Annually (minimum size 55mm).	Preference 12-18 °C, known temperature linked distribution and abundance shifts.
Blue Crab (Chesapeake Bay, USA)	Sex-Specific Age-Structured Model	Stock is variable. Currently above the threshold of 72.5 million individuals but below the 196 million target.	Recruitment variable. Recruitment was estimated at 86 million individuals in 2021, which was a decrease in the time series.	For the Chesapeake population, overwintering behavior between 3 - 10 °C. Mortality occurs below 3 °C and above 31 °C.
Blue Swimming Crab (Indonesia)	Surplus Production Model, Length Based Model	Stock status is over-exploited in 4 out of 7 FMA regions.	Fluctuating, variable but believed to be increasing in recent years. Data-limited, not much recruitment information is known.	Preference 28.5-31.5 °C, known temperature linked migration and size at maturity changes
Brown Shrimp (Gulf of Mexico, USA)	Stock Synthesis Assessment Model	Spawning biomass and recruitment are decreasing while fishing mortality increases. If this pattern continues at the current rate, overfishing may become evident	Fluctuating, decreasing in recent years. As of 2016, over 17.3 billion individuals.	Adults: 10-37 °C, known temperature linked distribution, abundance, and growth changes
Dungeness Crab (USA)	No Formal Assessments, Catch-based index of Abundance	Landings are annually variable, however stable over long trends. No stock status exists outside of landings trends.	Recruitment is highly variable, changes in atmospheric forcing drive differences in the annual number of megalopae, strongly influencing year class size	Preference 8-15 °C, Megalopae are highly influenced by seasonal climate shifts.
Northern Shrimp (Greenland)	Schaefer production model	Stock had been declining in the early-mid 2000's, but now appears to be well above MSY level	Recruitment assessment based on indices of age -2 shrimps (10.5-13.5mm carapace length) and pre-recruits (14-16.5mm carapace length). Fluctuating at relatively low levels with pulses of recruitment in 2015 and 2017	Preference -1°C to 6°C bottom temperature, known temperature links to abundance.
Northern Shrimp (Gulf of Maine, USA)	Catch-at-Length Model with Traffic Light Approach	Fishery under moratorium since 2014 due to continuously low stock abundance.	Annual recruitments have trended downwards and are likely lower than previous years	Gulf of Maine northern shrimp stock are the southernmost extent of this species and highly sensitive to changes in temperature regimes
Snow Crab (USA)	Size-Structured Model	Recently biomass was increasing again, but in 2022 the stock is at a new all-time low and 40% less than the previously all-time low seen in 2021	Low recruitment early 1990s-2014. Large year class recruited in 2015 but has now disappeared before reaching commercial size.	Require temperatures less than 5°C, and prefer waters less than 2°C. Warming trends appear to have contributed to the recent collapse of the eastern Bering Sea snow crab
Spiny Lobster (Indonesia)	Surplus Production Model, Length based Model	Stock assessments are specialized to specific regions and species. In general spiny lobsters are heavily exploited.	Indonesia benefits from high regional Puerulus stage juvenile lobster settlement, however formal assessments of recruitment are data limited.	Preference 27-30 °C, growth tightly linked to temperature.

Table 5: Empirical reference points (abundance, CPUE, and landings) and biological reference points (see Table 1 for definitions) in relation to nine crustacean fisheries case studies (see Figure 1 for location specificity), ranked by landings time series length and intensity of sampling as an approximation of overall data availability. Checks in blue signify a reference point actively used in a fishery management plan, and red checks are BRPs available in the literature but not actively used for management.



Species Name (Location)	**Empirical Reference Points**			**MSY**	**BMSY**	**FMSY**	**FMAX**	**F0.1**	**FX% - SPR**	**Z**
	Abundance	***CPUE***	***Landings***							
American Lobster (USA)	X	X	X	X			X	X	X	X
Blue Crab (Chesapeake Bay,	X	X	X	X *uMSY*		X			X	
Blue Swimming Crab (Indonesia)	X	X	X	X		X			X	X
Brown Shrimp (Gulf of Mexico, USA)	X	X	X	X *SSBmsy*		X				X
Dungeness Crab (USA)		X	X							
Northern Shrimp (Greenland)	X	X	X	X	X	X		X		X
Northern Shrimp (Gulf of Maine, USA)	X		X							
Snow Crab (USA)	X	X	X	X	X	X	X	X	X	X
Spiny Lobster (Indonesia)	X	X	X	X	X	X			X	X

Blue: Used in management decisions/assessment. Red: Provided in scientific literature but not used in management (Due to poor suitability for species, or management integration)

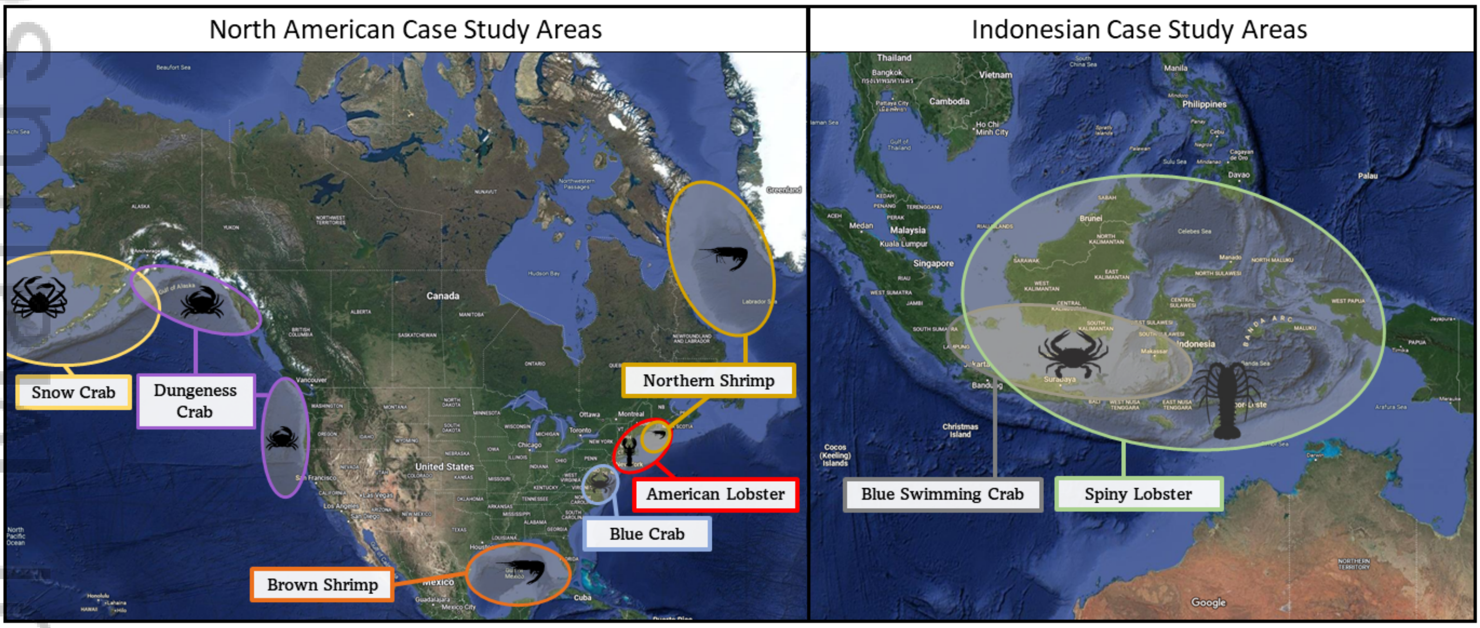


Figure 1 Study Area.png

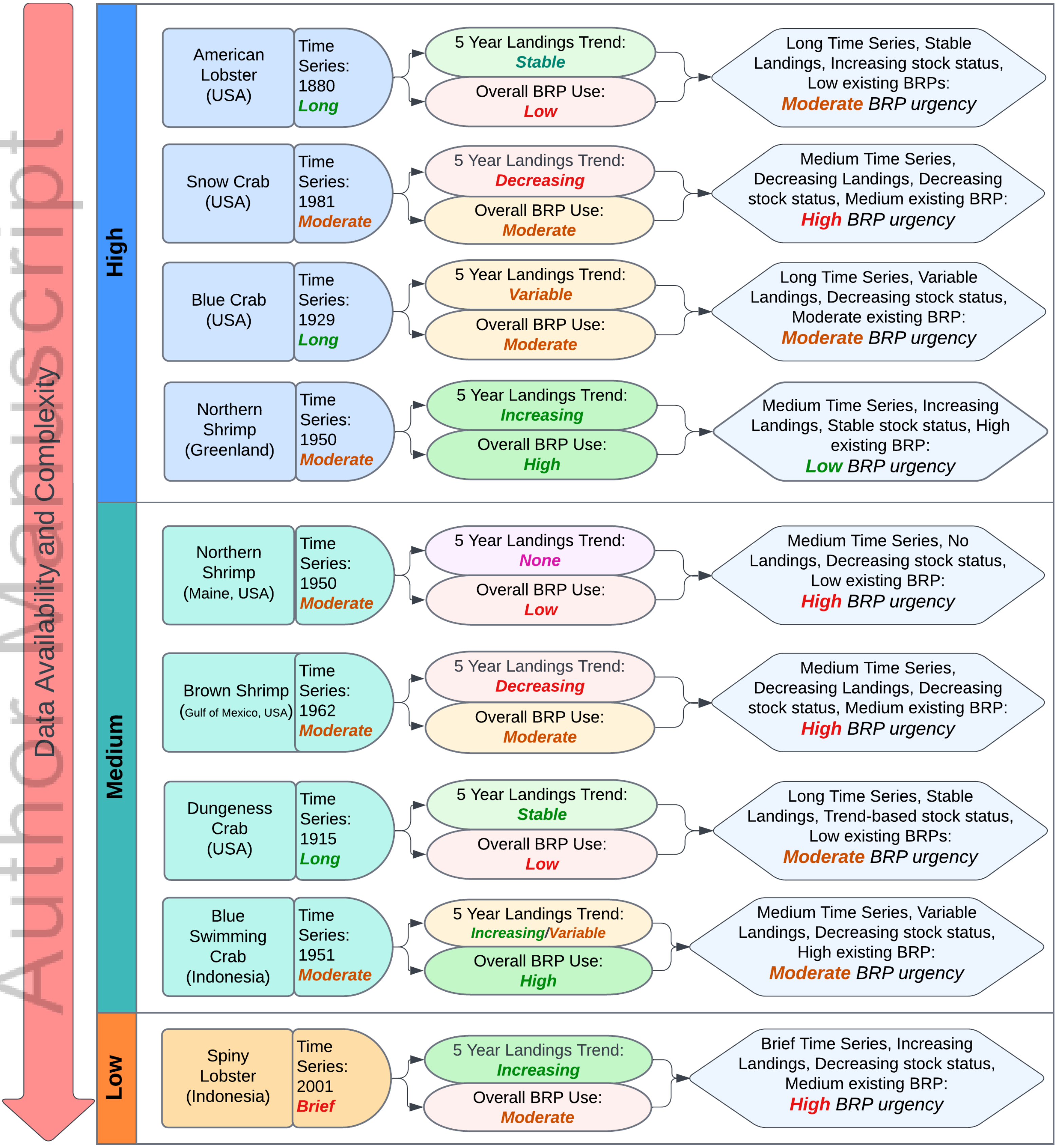

Data Availability and Complexity
High
Medium
Low
American Lobster (USA)
Time Series: 1880 Long
5 Year Landings Trend: Stable
Overall BRP Use: Low
Long Time Series, Stable Landings, Increasing stock status, Low existing BRPs: Moderate BRP urgency
Snow Crab (USA)
Time Series: 1981 Moderate
5 Year Landings Trend: Decreasing
Overall BRP Use: Moderate
Medium Time Series, Decreasing Landings, Decreasing stock status, Medium existing BRP: High BRP urgency
Blue Crab (USA)
Time Series: 1929 Long
5 Year Landings Trend: Variable
Overall BRP Use: Moderate
Long Time Series, Variable Landings, Decreasing stock status, Moderate existing BRP: Moderate BRP urgency
Northern Shrimp (Greenland)
Time Series: 1950 Moderate
5 Year Landings Trend: Increasing
Overall BRP Use: High
Medium Time Series, Increasing Landings, Stable stock status, High existing BRP: Low BRP urgency
Northern Shrimp (Maine, USA)
Time Series: 1950 Moderate
5 Year Landings Trend: None
Overall BRP Use: Low
Medium Time Series, No Landings, Decreasing stock status, Low existing BRP: High BRP urgency
Brown Shrimp (Gulf of Mexico, USA)
Time Series: 1962 Moderate
5 Year Landings Trend: Decreasing
Overall BRP Use: Moderate
Medium Time Series, Decreasing Landings, Decreasing stock status, Medium existing BRP: High BRP urgency
Dungeness Crab (USA)
Time Series: 1915 Long
5 Year Landings Trend: Stable
Overall BRP Use: Low
Long Time Series, Stable Landings, Trend-based stock status, Low existing BRPs: Moderate BRP urgency
Blue Swimming Crab (Indonesia)
Time Series: 1951 Moderate
5 Year Landings Trend: Increasing/Variable
Overall BRP Use: High
Medium Time Series, Variable Landings, Decreasing stock status, High existing BRP: Moderate BRP urgency
Spiny Lobster (Indonesia)
Time Series: 2001 Brief
5 Year Landings Trend: Increasing
Overall BRP Use: Moderate
Brief Time Series, Increasing Landings, Decreasing stock status, Medium existing BRP: High BRP urgency

Figure 2.png