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Merits of Multi-Indicator Precautionary Approach Management in a Male-Only Crab Fishery

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Abstract: Snow crab replaced groundfish fisheries as the primary focus of the Newfoundland and Labrador (NL) fishing industry in the mid-1990s. Over the past three decades, management philosophies in this male-only fishery have shifted from promoting industry expansion to promoting industry rationalization to implementing Precautionary Approach (PA) management. Until the mid-2010s, there were regionalized management strategies characterized by higher exploitation rates in northern than southern sub-stock units along the NL marine shelves. However, in the late 2010s, exploitation rates were permitted to elevate to high levels across the entire stock range in association with a large resource decline, and evidence of biological harm through fishing emerged in chronically depleted areas. In 2019, when stock and fishery productivity were near historical lows, a multi-indicator PA system was informally introduced into the management of the resource. This event coincided with anticipated improvements in stock and fishery performance. This paper examines the extent to which the multi-indicator PA management system, focused on the promotion of both biological protection and maximization of fishing efficiency, may have contributed to recent improvements in stock and fishery status. A suite of indicators from areas implementing PA guidance into management in 2019 prior to the formal adoption of the PA system in 2023 suggest the system has been highly beneficial in promoting rapid recovery and improving stock and fishery performance metrics to levels matching or exceeding historical levels under similar conditions. We discuss the capacity of the system to better safeguard biological aspects of resource and fisheries productivity moving forward under a scenario of an expectant resource decline.

Keywords: snow crab; Newfoundland and Labrador; fisheries management; Precautionary Approach; male-only fishery

Key Contribution: Multi-indicator Precautionary Approach management systems in male-only crab fisheries can effectively promote sustainable management by providing an additional benefit of efficient resource extraction along with the protection of reproductive capacity.

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1. Introduction

1.1. History of the Fishery

The collapse of groundfish stocks and shuttering of fisheries off Newfoundland and Labrador (NL), Canada (Figure 1) in the early 1990s is commonly cited as an example of overfishing consequences (i.e., [1]). The closure of the Atlantic cod (*Gadus morhua*) fisheries in 1992 led to 30,000–40,000 displaced workers [2,3] and forever changed the complexion of a fishery that had underpinned 500 years of colonization of Newfoundland and Labrador since European discovery in 1497.

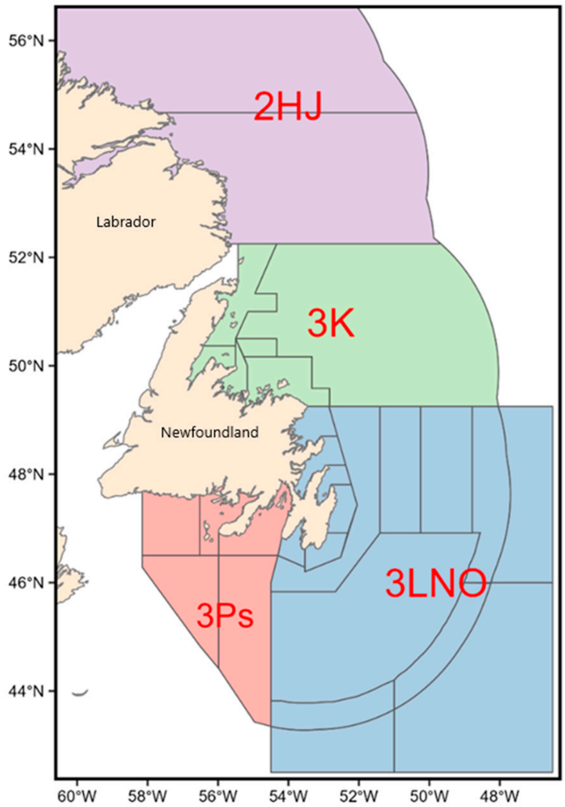

Figure 1. Map of Newfoundland and Labrador snow crab Assessment Divisions (AD) 2HJ, 3K, 3LNO, and 3Ps used in the analysis. Black lines show Crab Management Areas (CMAs).

While a high level of scientific and social focus continues to be placed on factors leading to the collapse and slow recovery of groundfish stocks, comparatively little focus occurs on fisheries that emerged post-collapse. The primary fisheries in the three decades since groundfish collapses have targeted snow crab (*Chionoecetes opilio* (Fabricius, 1788)) and northern shrimp (*Pandalus borealis*), with the snow crab fishery overall dominant in supporting rural areas of the Province because the stock is distributed off all NL coasts, generally more feasible, and usually more lucrative. The NL snow crab fishery has represented the largest global supply for the species for the past three decades and enabled unprecedented economic prosperity for the NL fishing industry.

Changing philosophies regarding the activity and management of the NL snow crab fishery have partitioned the past five decades into distinct periods. Despite long-standing lucrative fisheries of snow crab in areas such as Alaska and the Gulf of St. Lawrence, little interest in fishing snow crab occurred in NL prior to groundfish collapses. Small-scale directed fishing has been documented back to the late 1960s [4,5] at the start of what we term the Infancy Period (Table 1), but as it became apparent that the snow crab stock was large enough to support a large-scale fishery in the wake of groundfish collapses, rapid fishery expansion ensued during 1992–1999 and the fleet ballooned from several hundred to nearly three thousand vessels. Herein, the Infancy Period is deemed to end in 1991, and the 1992–1999 timeframe is termed the Expansion Period. The Expansion Period was characterized by competition for access and allocation rights [6] and ultimately led to the complex spatial management system characterized by many small management areas within the broad biological stock complex to control fleet dynamics (Figure 1). The stock is assessed at the Assessment Division (AD) level and managed at the Crab Management Area (CMA) level (Figure 1).

Table 1. Chronology of time periods of important changes in stock, fleet, and management dynamics in the Newfoundland and Labrador snow crab fishery.

Years	Period
late 1960′s–1991	Infancy
1992–1999	Expansion
2000–Present	Rationalization
2000–2018	Mature–Senescent
2019–2022	Informal PA
2023–Present	Formal PA

In 1999, the highest-ever quota for NL snow crab (69,000 t) was set and captured. However, stock assessment scientists immediately began documenting a resource decline and expressing concerns about the forthcoming potential for overfishing [5,7]. Management philosophy shifted from one supporting rapid fishery expansion to one recognizing fleet over-capacity [8] and progressively implementing rationalization measures to remove vessels from the fishery. These included initiatives to permanently ("Enterprise Combining") or temporarily ("Buddy-up") reduce fishing occurring from multiple vessels down to a single vessel [9], with the overall reductions in trap limits serving to reduce the fishing power of the fleet. This post-1999 period is termed the Rationalization Period in this analysis and is still ongoing.

During 2000–2018, as rationalization ensued, the fishery and management system progressed into what could initially be described as a maturation stage. The stock range was fully exploited, with quotas being set based on a co-management system incorporating harvester recommendations alongside index-based stock assessments [9,10]. However, increased biological knowledge also accrued during this period, and it became progressively clearer that the ecosystem carrying capacity was dissipating and that the stock was on a declining trajectory. In 2014, formal scientific warnings were given that a large decline in exploitable biomass was imminent and the industry should prepare [11,12]. However, despite lead time, overall fishery exploitation rates (landings/biomass of legal-size males) were enabled to further increase to unprecedented highs during 2016–2018, while the stock was in its lowest biomass state. In 2016, the exploitable biomass of the stock had shrunk to just 9% of its highest measured level in 1996, and males in areas chronically fished at high exploitation rates began to show declines in size-at-maturity (SaM; synonymous with size-at-terminal molt) in response to low population densities [13]. The fishery had progressed beyond a mature stage and into a senescent state, and unprecedented quota cuts occurred. Henceforth, the 2000–2018 timeframe is referred to as the Mature–Senescent Period.

In 2018, a multi-indicator Precautionary Approach (PA) management framework was introduced [14]. This did not occur in response to the poor stock and fishery state; rather, the timing was coincidental, with the system under development since 2012. The development of a PA management system occurred in response to fulfill both a processing sector request to meet eco-certification requirements and a Fisheries and Oceans Canada (DFO) mandate to implement PA systems into the management of major commercial fish stocks. The primary goal of this analysis is to explore the extent to which the introduction of this multi-indicator PA management system may have contributed to stock and fishery improvements since 2018.

The base system identified metrics for the development of a holistic health score index as well as Limit Reference Points (LRPs) differentiating cautious and critical zones [14]. However, as per the DFO process, the base system required collaborative work with industry to develop reference points to differentiate cautious from healthy zones and Harvest Control Rules (HCRs) to guide management decision-making. Furthermore, the unique multi-indicator approach required collaboration on the development of a scoring matrix for the three health status metrics. Accordingly, the PA system was not implemented in 2018. The coincidental timing of the development of a PA system to guide stock management decisions alongside a fishery undergoing large quota cuts created a situation of considerable unrest within the industry. Extensive consultation occurred during 2019–2022, and during this time, management adopted the approach of using "the spirit of the PA" to help guide decision-making while the system was finalized. In 2023, the PA was formally applied for the first time in management decisions. Herein, 2019–2022 is termed the Informal PA Period, and post-2022 is termed the Formal PA Period.

1.2. Snow Crab Fishery Management

The focal biological feature underpinning snow crab management is sexual size dimorphism, which allows a sex-exclusive harvest of the larger sex (males). This exploitation strategy alone is precautionary in principle by helping safeguard reproductive capacity while prosecuting fisheries through full protection of females [15–17]. A second biological safeguard is sperm storage by females, whereby multiple year's egg clutches can be fertilized from a single season of mating [18]. However, biological harm can still be induced through fishing only males, in particular through size-at-maturity effects [13] or sperm limitation [19] if harvests too severely deplete the density of large adult males. Siddeek et al. [20] estimated the fishing mortality rate producing the maximum sustainable yield (f_{msy}) in major snow crab stocks to be in the range of 26–42% annual harvest of the exploitable biomass of large males. Overall, species biology leads to fundamental approaches of using large-mesh traps to eliminate females and small males from the catch and consistent application of low to moderate exploitation rates to maintain enough large males to promote intraspecific competition in the population as the key regulatory strategies to promote a sustainable harvest.

A second management-related outcome affected by fishery exploitation rates is discarding mortality. Components of males in the population discarded in the NL snow crab fishery are those that are either soft-shell (recently-molted) or sub-legal-size (legal-size is 95-mm carapace width (CW) in NL). Discard mortality rates in either group are not fully understood but are likely affected by a myriad of factors, including time out of water, air and water temperature, wind speed, sunlight, and individual size and shell condition [21–25]. Discard mortality rates are likely highest on soft-shell crab [26], which are most apt to appear in summer fisheries following winter–spring molting as recently molted crab become more mobile. An interaction of exploitation rates and seasonality governs the incidence of soft-shell crab in a catch, with low exploitation rates and winter fishing being the most optimal in minimizing discards [26]. However, fisheries can maintain low levels of discards throughout the year, even in summer, if exploitation rates on large males are consistently kept low. The negative relationship between exploitation and discard rates leads to a hypothesis that low exploitation rates help keep enough large males around to maintain sufficient competition and exclude less competitive crab from trapping. Another potential advantage of the exclusion of soft-shell crab from trapping is reduced mortality through cannibalism within active fishing traps.

1.3. Overview of NL Snow Crab PA System

PA systems focused on finfish overwhelmingly focus on spawning stock biomass toward maintaining reproductive capacity in fisheries targeting both sexes [27,28]. Typically, reference points to differentiate stock status are established within a range of historical spawning stock biomass levels. In snow crab, given the important role of large males in affecting insemination rates in females [29,30], the sole focus on the exploitable biomass of males can be justified as the basis of PA management frameworks [31]. However, given the simplicity with which the major precautionary measure of a male-only harvest can be implemented, it is also convenient and appropriate to extend PA management systems on snow crab into ancillary population or fishery performance considerations toward applying a more holistic management system to supplement the central male-only harvest strategy [27,28].

The multi-indicator PA management system used for NL snow crab invokes an additional objective of maximizing fishing efficiency along with the typical objective of assuring biological protection of the resource as its over-arching philosophies [14,28]. The three metrics used to address these objectives are predicted fishery CPUE (*pCPUE* [kg/trap]), predicted fishery discards (*pDIS* [%]), and proportion of mature females carrying full clutches of viable eggs (*EGG* [α]). The three metrics are weighted within a scoring matrix that produces a range of outcomes for an "integrated health score" ranging from 0 to 7. Maxima of 4, 2, and 1 health points are awarded for the *pCPUE, pDIS, and EGG* metrics, respectively, depending on performance relative to reference points established for each metric. The scoring matrix was established collaboratively between industry, management, and science, and among other considerations, weightings reflect the ability of management measures to directly affect outcomes of each metric (i.e., most direct effect on *pCPUE*), as well as dynamic data ranges within historical time series for each metric (i.e., most stability in *EGG* index). Upon summation, the integrated health score index is differentiated into healthy (5.5 to 7), cautious (2.5 to 5), and critical (0 to 2) zones. The HCRs for exploitation rates are defined as ranges with minima of 0% and maxima of 42%, 35%, and 20% for the healthy, cautious, and critical zones, respectively. The use of ranges to define HCRs for each zone rather than explicit levels allows flexibility for management and industry to consider a broader suite of factors (i.e., socio-economic) in formulating annual harvest rate strategies.

2. Materials and Methods

2.1. Background

This paper serves to evaluate the extent that the development and application of a multi-indicator PA system into the management of NL snow crab may have contributed to recent changes in stock and fishery performance. In doing so, this analysis evaluates progressive work and experiences in PA system development [14,17,28] along with the integration of the PA system into stock status assessments [32,33] and indirectly or directly evaluates its performance in relation to past outcomes of deleterious impacts of overfishing in NL snow crab including high discard rates [26], size-at-maturity shifts [13], and sperm limitation [19]. Accordingly, many non-novel aspects of forthcoming Sections 2.2–2.4 are intentionally kept succinct due to more thorough documentation of relevant information in the existing literature.

2.2. Fishery Data

Time series of numbers of active vessels, fishery landings (metric tonnes), and fishery effort (trap hauls) for the four focal ADs of the NL shelf were examined in the context of important periods of growth and decline and changes in management philosophies in the fishery (Table 1). The number of active vessels was determined from DFO databases of commercial logbooks and landings offloads, identifying unique Vessel Registration Numbers (VRNs) present in the databases annually for each AD. Data on VRNs were incomplete during some years (1995–1997) within the Expansion Period.

Landings were enumerated by a dockside monitoring program and summed by year for each AD. Fishery CPUE was calculated from commercial logbook data and standardized for spatial and temporal distributions and trap soak times (hours) in a generalized linear mixed model in the *lme4* package [34] in R [35]. Logbook return rates have consistently exceeded ~80% of fishing trips in each of these ADs since 1996. The CPUE standardization model regresses square root transformed CPUE (sqrtcpue) against fixed effects of calendar day (day) and trap soak times (soak), with random slopes and intercepts (1) between square root CPUE and for combinations of year, CMA, and AD.

$$\text{sqrtcpue} \sim (1 + \text{day} + \text{soak} + (1 + \text{day} \mid \text{year:CMA:AD})) \quad (1)$$

Total fishery effort estimates (# of trap hauls) for each AD and year were calculated as the quotient of the division of landings by standardized fishery CPUE. Each fishery index (landings, CPUE, effort) was examined in the context of periods of changes in management philosophy in the fishery for which data sufficed.

Fishery discard rates were estimated from at-sea observer data, with in-season measurements of the catch beginning in 1999. Observers are onboard personnel who monitor for regulatory compliance and take biological measurements of the catch [9,32]. Observer coverage in the fishery is typically low (i.e., <5% of trips per year), with 0.05–0.6% of the annual catch measured within these ADs. In line with low coverage levels, observer deployments follow a random sampling design across time (weeks) and space (CMAs) to ensure data collections are as representative as possible. The PA management system focuses on minimizing all discards. Observer measurements of sub-legal-size males, soft-shell males, and all females were considered discards, with all other measured crab considered kept. The discard standardization model Equation (2) is a binomial generalized linear mixed model fit in the *lme4* package relating the number of crab discard occurrences (tdisc) out of the total number of discards plus kept crab (ttot) in any given sampling event to the same predictors in Equation (1).

Since 2019, all ADs have received particularly low observer coverage (i.e., $\leq$0.1% of the catch measured); thus, the discard standardization model Equation (2) is only fit up to 2019. Post-2019 predictions of discard rates assume they will reflect those that occurred under similar conditions in the model predictor terms (calendar day, soak times, CMA, and AD) during 1999–2019. Although post-2019 observation data are not used to fit the standardization model, an index is used to qualitatively assess the model's performance. This post-2019 index of annual observation data for discards is an average of estimates from observer measurements and logbook-recorded estimates from an anonymous select group of vessels historically showing tight conformity to observer estimates (i.e., a "reference fleet").

$$\text{tdisc/ttot} \sim 1 + \text{day} + \text{soak} + (1 + \text{day} \mid \text{year:CMA:AD}) \quad (2)$$

2.3. Exploitable Biomass Estimation

The Exploitable Biomass Index (EBI) is defined as the biomass (metric tonnes) of male crab $\geq$ 95 mm CW. The index is derived from annual multispecies trawl surveys that occur on DFO research vessels in fall (September–December, beginning in 1995) in ADs 2HJ, 3K, and 3LNO, and in spring (April–May, beginning in 1996) in AD 3Ps. The surveys are conducted within a depth-stratified sampling design of the NL marine shelves [36]. Set allocation is proportional to the size of each survey stratum. The trawl itself is a Campelen 1800 rockhopper shrimp trawl (14" rockhopper footgear) [37] and is towed for 15 min duration at 3 knots when conditions allow, with snow crab catch rates standardized to the swept area of 15-min tows. In most years, about 600–700 tows would cover the marine shelves of ADs 2HJ, 3K, and 3LNO in the fall, and about 150–175 tows would cover the AD 3Ps shelf in the spring. In 2023, two new identical research vessels were introduced as the primary trawlers, and conversion factors developed for snow crab [38] were applied to the historical time series to bring historical data on abundance into the same scale as those derived from the new trawlers.

In the 3Ps time series, the multispecies surveys were incomplete in 2006 and fully missed in 2020 and 2023. In the fall time series, AD 3LNO had an incomplete survey in 2021, and surveys in all ADs (2HJ, 3K, and 3LNO) were missing in 2022. This complete omission of fall surveys in 2022 was associated with comparative fishing experiments among old and new trawlers taking precedence over routine monitoring surveys.

Despite incomplete and missing multispecies trawl surveys, a cohesive time series EBI can be estimated for each AD. In the cases where grounds are partially covered by survey tows, such as in comparative fishing experiments, biomass is estimated in the R package *sdmTMB* [39], whereby generalized linear mixed models are estimated across spatial and temporal domains from geostatistical time series data, effectively integrating historical spatial–temporal survey catch rate information with existing coverage to estimate biomass. Time, location, and depth are used to predict survey catch rates in missing areas. This approach has been validated by comparisons to independent trap surveys in each AD, which consistently produce very similar results to the model-generated estimates for the trawl index. In cases where trawl surveys are fully missed, trap survey estimates are used as the basis for the EBI. The scaling of trap survey biomass estimates into comparable trawl survey biomass units is achieved through comparisons of both surveys to a third measure of exploitable biomass derived from DeLury catch rate depletion modeling [40] of fishery CPUE throughout the season to estimate the beginning of season biomass, deriving independent adjustment factors to scale each survey time series into common biomass units [32,33]. The trap surveys used for validation of model-based trawl survey biomass estimates only have usable time series since 2018 and thus are not focused on in this analysis, with the longer time series from trawl surveys preferred.

The Campelen trawl has a capture efficiency ("catchability") of less than 1 for all sizes of snow crab [41]; thus, model-based biomass estimates not adjusted by the DeLury scalar are underestimated. To expand on the particularities of the DeLury adjustment approach, along with producing beginning-of-season exploitable biomass estimates, DeLury biomass estimation relies on consistent depletion in fishery catch rates occurring throughout the fishing season; thus, it cannot be estimated every year. Both issues render DeLury biomass estimates unusable for real-time assessment and management of the resource. To construct an adjustment factor for the trawl (or trap) time series EBI, a one-year lag is applied in calculating the ratio of the preceding (typically fall) survey to subsequent (typically spring) DeLury biomass estimates wherever possible, and a time-series median of the annual ratios is used as the scalar to convert survey EBIs into realistic values. Ultimately, this process results in the trawl (or trap) survey shaping the EBI and the fishery-derived scalar determining the magnitude of the EBI. Accordingly, the EBI is deemed a realistic index but not an absolute estimation.

The exploitable biomass is affected by changes in productivity, which is measured through recruitment, as well as fishing, which is measured by exploitation rates. Two dominant components are defined in the exploitable biomass based on the shell condition of individuals, with the shell condition representing a proxy for time since molting. Crab of legal size that contribute to the exploitable biomass are often terminally molted adults, but if still adolescent and molting, would normally be on a near annual molting schedule [42,43]. Accordingly, those in a soft or new-shell condition are deemed to be recently molted and constitute immediate recruitment into the biomass. In contrast, crab in an intermediate or older shell condition are assumed to have molted at least one year ago and represent the residual biomass. This assumption holds most rigidly for terminally-molted crab, which normally comprise the majority of the exploitable biomass [44]. The proportion of the exploitable biomass comprised of residual crab was examined as an indicator of population health. Large, residual males are the most competitive crab in the population and help maintain hierarchical intrinsic competition, encourage the growth of individuals to large sizes, and promote the reproductive health of the stock [13,19]. From a fisheries perspective, large, residual males help offset the incidence of soft-shell crab capture in the catch due to associated competition exclusion for access to baited pots [26].

A two-period moving average is applied to EBI for each AD to estimate fishery exploitation rates. This is performed due to historical concerns of year effects in the trawl survey time series [32]. Further, in the context of the PA framework used to provide advice on outcomes of the forthcoming fishery, the predicted fishery CPUE metric maintains correlations to the EBI from multiple preceding surveys (i.e., lags of 1–3 years), not just the most recent biomass estimate [14]. The Exploitation Rate Index (ERI) is calculated as fishery landings in a given year (y) divided by the two-period moving average estimate of EBI preceding the fishery (y − 1) Equation (3).

$$\mathrm{ERI} = \mathrm{landings}\ (\mathrm{y})/\mathrm{EBI}\ (\mathrm{y}-1) \tag{3}$$

2.4. PA Management System Bases and Models

Similar to most PA management systems, one of the main features of the multi-indicator PA management system used in NL snow crab is that it imposes limits on fishery

ERIs. Bases for the efficacy of performing this were examined through relationships of ERIs versus proportions of residual biomass in the population and soft-shell crab in the catch, contrasting rates of each metric across ADs. For each AD, cumulative ERIs, cumulative proportions of residual biomass, and cumulative proportions of soft-shell crab measured by observers were calculated for the 1999–2019 period. This period was chosen because observer measurements did not begin until 1999, and there were poor levels of observer coverage and an increased incidence of missing surveys after 2019. Slopes of linear regression models fit through the origin for each cumulative curve were used to quantify average rates of each metric over the time period. Subsequently these regression slopes were applied as data to examine relationships among the three variables in simple linear regression models.

The PA management system uses predicted fisheries CPUE (*pCPUE*) as a focal metric for helping managers and harvesters plan for likely fishery performance outcomes in the forthcoming season under different catch scenarios. This approach capitalizes on a strong relationship between lagged fishery CPUE versus exploitable biomass. The *pCPUE* model is a generalized additive mixed model fit in the *mgcv* package [45] in R. It regresses standardized fishery CPUE (st_cpue) against predictor variables of fishery ERI, the two-year moving average EBI (BIO) from trawl surveys (1995–2017) or an average of trawl plus trap surveys (2018–2023), an annual index of the North Atlantic Oscillation (NAO) from seven years prior (NAO7), and random effects of AD and year, treated as a factor variable Equation (4). NAO7 is included due to the strong positive correlation of future exploitable biomass with this climate system at lags of 6–8 years [14,46]. A thin-plate smoothing spline (s) is included on all fixed effects, with the exception of ERI. The number of smoothing knots is depicted by k and be='re', which indicates a random factor effect. The ERI term is simulated under various quota scenarios to predict outcomes of fishery CPUE under different management options.

$$\text{st\_cpue} \sim \text{ERI} + \text{s(BIO, k = 6)} + \text{s(NAO7, k = 6)} + \text{s(AD, bs = 're')} + \text{s(year, bs = 're')} \quad (4)$$

The second focal metric in the multi-indicator PA management system is predicted discards (*pDIS*), with the system aiming to minimize fishing mortality caused by discarding. The *pDIS* model is a generalized additive mixed model fit in the *mgcv* package that regresses the response variable of the standardized percentage of the catch discarded (st_dis) against predictor variables of *pCPUE* Equation (4), median fishing day (mFD), the ratio of exploitable to pre-recruit crab in the population in the previous year (EP1), and a random effect of AD Equation (5). A thin-plate smoothing spline (s) is included on all effects. The *pCPUE* term extends the simulation of outcomes from different quota scenarios into predicting fishery discards, while the median fishing day is set to the previous year's value to predict outcomes of discards under status quo fishery timing. The ratio of exploitable to pre-recruit crab is an index of the buffering capacity of the population to offset captures of small males or soft-shell crab, with an index favoring exploitable males associated with high buffering capacity. Pre-recruits are defined as 70–94 mm CW adolescent males and have the potential to be captured in the forthcoming fishery either in the form of under-sized males or soft-shell legal-size males, depending on whether or not they molt and the size of the growth increment if they molt.

$$\text{st\_dis} \sim \text{s(pCPUE)} + \text{s(mFD)} + \text{s(EP1)} + \text{s(AD, bs = 're')} \quad (5)$$

The final focal metric in the multi-indicator PA management system is the proportion of mature females in the population carrying full clutches of viable eggs (*EGG*). This metric serves as an index of stock reproductive capacity in light of only removing males through fishing. While the multispecies trawl surveys provide the only long-term time series of broad-scale survey data available for resource assessment processes such as biomass estimation, other survey series comprised of localized trap surveys conducted by DFO in inshore bays of Newfoundland and trap surveys conducted through collaborations with industry groups throughout ADs 2HJ, 3K, 3LNO, and 3Ps, provide data useful for other purposes such as the examination of fecundity in females. All trap surveys include small-mesh traps (1″ mesh) that capture sub-legal-sized crab, including females. Given the focus is on proportional (not absolute) levels of female fecundity, data from females captured in all trap and trawl surveys are used to quantify this metric. The assessment of relative clutch levels is based on a visual examination of the abdomen, with incremental classifications used to quantify egg clutch fullness. Mature females assessed as having a full brood (i.e., eggs protruding beyond the abdominal flap) of healthy-looking eggs (i.e., orange vs. brown or black) or showing evidence of recently releasing healthy-looking eggs (i.e., remnants of a clutch still apparent) are classed as having full clutches of viable eggs.

2.5. PA Management System Performance Assessment

The performance of the PA management system was judged during the 2019–2023 period. System performance was assessed based on trends in the three focal PA metrics, *pCPUE*, *pDIS*, and *EGG*, along with trends in two ancillary metrics of the proportion of the exploitable biomass comprised of residual crab as well as an index of male SaM. The residual biomass proportions metric was fit with loess regression curves to partially account for missing or different (i.e., comparative fishing) survey types in some years. For investigation of "stock-level" analyses of fishery CPUE, ERIs, and residual biomass proportions, boxplots were used to investigate contrast across ADs. In contrast, data for each AD were additively pooled to form annual point estimates of each index.

The SaM performance metric was included because of the downward shift in SaM concurrent with the heavy exploitation preceding the Informal PA Implementation Period [13]. With the omission of trawl surveys in recent years, this index had not been updated; thus, it was unknown if the PA system was having any influence on the phenomenon. The model used to estimate the proportion of mature crab (pMAT) was a generalized additive model fit in the mgcv package. It was fit to recently-molted males (soft or new-shell crab), with sizes binned to 10-mm CW increments Equation (6).

$$\text{pMAT} \sim \text{te}(\text{CW}, \text{year}, \text{k} = 11, \text{by} = \text{AD}) \tag{6}$$

The model incorporated the interaction of carapace width (CW) and year as predictor variables, and the shape of the non-linear relationship was allowed to vary separately for each AD. The interaction term was constructed as a tensor product smoother (te), and a weighting term of size-specific sample size was included to offset influences of small sample sizes in AD and -year-specific size bin groupings. The model family was quasibinomial to help control for influences of 0 and 1 values in the binomial form data.

The performance metric was expressed as the size at which 50% of individuals were predicted to become mature in any given AD and year, with this "mat50" index commonly used in fisheries resource assessments.

3. Results

3.1. Fishery Data

The number of active vessels increased from 36 to 430 between 1988 and 1991 and to a maximum of about 2700 in 1998–1999 during the Expansion Period (Figure 2). Both the pre- and post-Expansion Period fleet sizes were largest in AD 3LNO (Figure 1), where about 1200 vessels were active in 1998. Rationalization of the fleet has progressively occurred in all ADs since 1998–1999, with a total of 1328 vessels active in 2023 and approximately 600 of those in AD 3LNO.

Overall fishing landings increased by a factor of four from 1992 (16,199 t) to 1999 (67,503 t) in ADs 2HJ, 3K, 3LNO, and 3Ps, with AD 3LNO accounting for 40–50% of the landings each year (Figure 2). Since the 1999 peak, landing trends have differed markedly across ADs, with the most contrast across ADs 2HJ and 3LNO. AD 2HJ has undergone a prolonged progressive decline to just 885 t in 2023, while the expansion of landings in AD 3LNO to 34,945 t in 2015 occurred following the initial adjustment to 26,816 t in 2000.

Since the Informal PA Period began, landings in ADs 3LNO and 3Ps have increased to near historical highs and recovered back to near the long-term average, approximating 10,000 t in AD 3K. Meanwhile, they have reached post-Expansion Period lows in AD 2HJ. Overall, landings about doubled from 26,187 t in 2019 to 51,169 t in 2023. Trends in the effort have loosely conformed to landings, although peak levels occurred later than 1999 (2003–2004) in all ADs. The overall peak level of 7.03 million trap hauls in 2004 contrasts a post-expansion era low of 2.71 million trap hauls in 2020 and a near-average level of 3.92 million trap hauls in 2023. The overall fishery CPUE levels in 2021–2023 (range 12.3 kg/trap to 13.6 kg/trap) are the three highest levels recorded since the 1996–2001 period (range 11.6 kg/trap to 14.1 kg/trap).

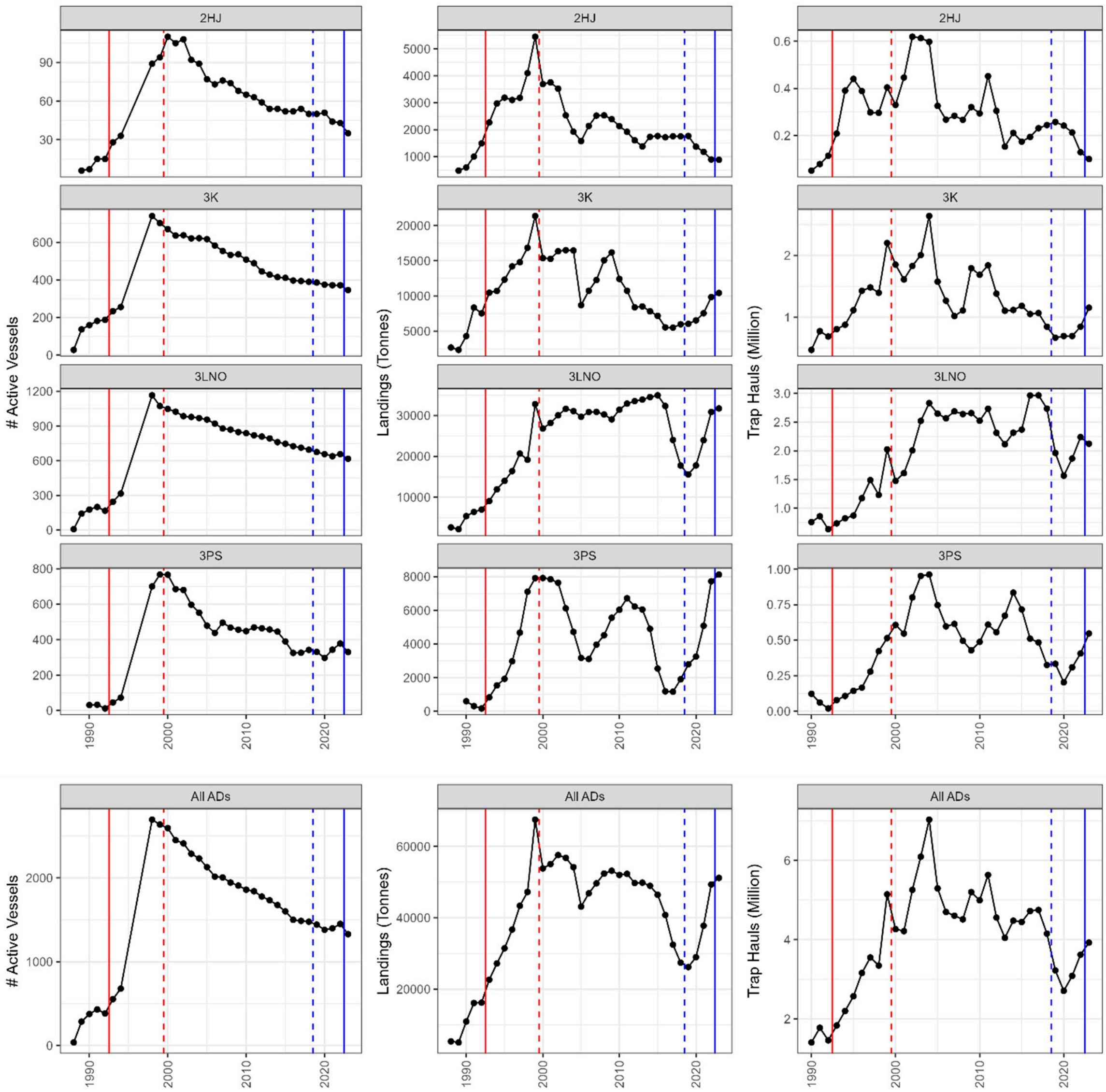

Figure 2. Number of active vessels (**left panels**), recorded landings (**middle panels**), and estimated trap hauls (**right panels**) in the snow crab fishery by year and Assessment Division. All ADs pooled in bottom panels. Vertical lines show the starts of the groundfish moratorium (solid red), Rationalization Period (dashed red), Informal PA Period (dashed blue), and Formal PA Period (solid blue).

The overall high fishery CPUE levels of 1997–2001 reflected sporadic or sustained incidences of high catch rates in all ADs and were associated with historical highs in the EBI (Figure 3). The overall pattern in the EBI, which averaged 325 kt from 1996 to 2001, is primarily driven by AD 3LNO in all years, accounting for an average of 72% of the index (range 63–86%) in any given year throughout the time series. The overall EBI reached a historic low of just 42,176 t in 2016 and has since recovered to near the long-term average, approximating 170 kt in 2023. Trends in fishery CPUE have generally reflected the EBI at a lag of 1–2 years in all ADs since the fishery Rationalization Period began.

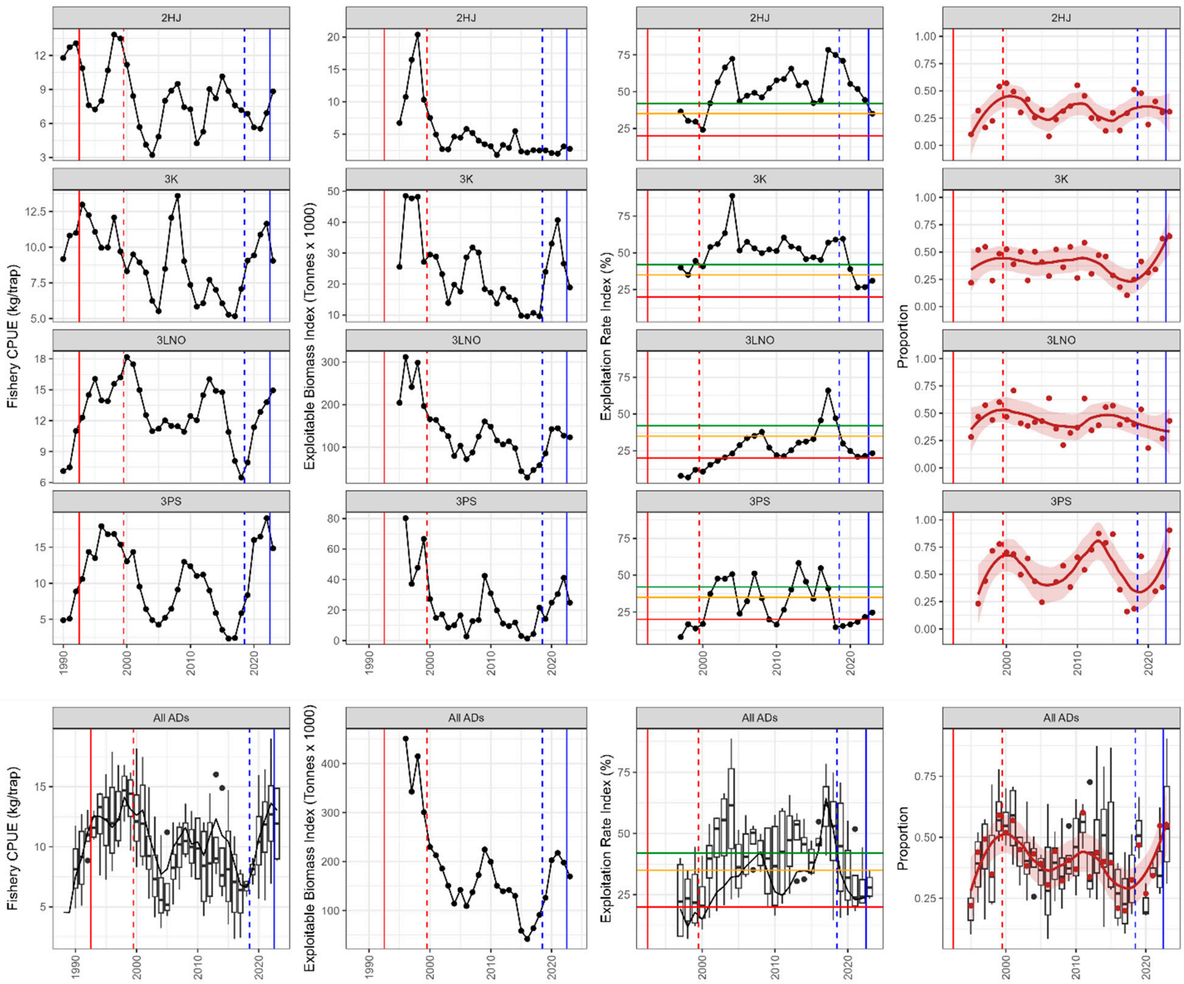

Figure 3. Trends in fishery CPUE (**left panels**), exploitable biomass indices (**left-middle panels**), exploitation rate indices (**right-middle panels**), and proportion of residual crab in the exploitable biomass (**right panels**) in the snow crab fishery and resource by year and Assessment Division. All ADs pooled in bottom panels. Loess regression fits (brown lines) and standard errors (brown shaded bands) fit proportions of residual biomass data (brown dots). In exploitation rate plots (right-middle panels), horizontal green, yellow, and red lines show the maximum allowable ERIs for healthy, cautious, and critical zones within the PA framework. Fishery CPUE and exploitation rate index plots in the All ADs (bottom) row boxplots show median levels across ADs along with the interquartile range (IQR, box) and 1.5*IQR (whiskers). In contrast, solid lines show indices based on pooled data. For the proportion of residual biomass in the All ADs row (bottom right panel), boxplots show levels across ADs while the loess regression line is fit to pooled data. Vertical lines show the starts of the groundfish moratorium (solid red), Rationalization Period (dashed red), Informal PA Period (dashed blue), and Formal PA Period (solid blue).

Overall, ERIs have been higher in ADs 2HJ and 3K than in 3LNO and 3Ps (Figure 3). During 2000–2018, in the Mature–Senescent Period, the ERI averaged 60%, 55%, 30%, and 37% annually in ADs 2HJ, 3K, 3LNO, and 3Ps, respectively. Since the Informal PA Period began, ERIs have been maintained at or near historical low levels, associated with allowable harvest rates for the cautious and critical zones, in all but AD 2HJ, where the ERI only dropped to below 42% and within the allowable range of the PA management system in 2023, when it was formally implemented. At a 35% harvest rate, the 2023 AD 2HJ ERI was set at the maximum allowable limit associated with its designation of being in the cautious zone. Overall, with data pooled, the stock-level ERI was unusually high in 2016–2018, reaching a peak of 64% in 2017. However, the index dropped substantially after 2018 and has remained steady at about 25% per annum in the past four years. When considering across-AD comparisons, the boxplot median levels of about 25–35% ERI occurring in the fishery in the past 4 years are the lowest levels occurring since the fishery Rationalization Period began.

3.2. PA Management System Performance Assessment

The proportion of the exploitable biomass comprised of residual crab has varied both across and within ADs over the time series (Figure 3). Overall, residual biomass proportions are lowest in AD 2HJ, where the loess regression model fit varied between 0.25 and 0.50 in most years. The loess index in AD 3K was relatively stable at about 0.4 until 2014 before dropping to a level closer to 0.25 from 2015 to 2018. It recovered to about the 0.4 level from 2019 to 2021 but has increased further to a level of 0.67-0.68 in 2022 and 2023. In AD 3LNO, the loess index of residual crab proportions in the exploitable biomass has varied between 0.35 and 0.55 throughout the time series. Overall, the highest variability has occurred in AD 3Ps, where the loess index of residual crab proportions in the biomass has fluctuated from 0.3 to 0.8. When data from all ADs are pooled, a pattern of increasing residual biomass proportions from 0.25 in 1995 to 0.5 in 1999–2000 occurred before a downward oscillation to a level of about 0.3 in 2016-2018. The index has increased every year since 2018, with values of greater than 0.5 in the past two years, producing a historical high in the loess model fit to these data.

The linear regression slopes of cumulative fishery ERI during 1999–2019, when observer data allowed for comparisons to soft-shell crab incidence in the catch, were 0.51 and 0.55 in ADs 2HJ and 3K, respectively, and 0.35 and 0.26 in ADs 3Ps and 3LNO (Figure 4). These levels were associated with lower regression slopes for proportions of residual biomass in the population in ADs 2HJ (0.35) and 3K (0.41) than in 3LNO (0.46) and 3Ps (0.58). Moreover, the higher average ERIs in ADs 2HJ and 3K were associated with much higher proportions of soft-shell crab measured in the catch in these ADs. The slopes of linear regressions fit to soft-shell crab proportions were 0.15 and 0.11 in ADs 2HJ and 3K, respectively, while they were just 0.03–0.04 in ADs 3LNO and 3Ps. The inverse direction of the relationship of ERI with residual biomass proportions in the population (R^2 = 0.39, slope = -0.45) versus soft-shell crab proportions in the catch (R^2 = 0.81, slope = 0.38) is consistent in depicting how high exploitation rates strip away the residual biomass and enable soft-shell incidence in the catch to become more problematic. In turn, a negative relationship between the proportions of residual biomass in the population and soft-shell crab proportions in the catch occurs (R^2 = 0.68, slope = -0.49).

Overall, the stock health status was poorest in 2017 when ADs 2HJ and 3LNO were in the cautious zone of the PA management system, and ADs 3K and 3Ps were both in the critical zone (Figure 5). Relatively abrupt improvements occurred thereafter in ADs 3K, 3LNO, and 3Ps, with each entering the healthy zone by 2021 and being maintained there since. Conversely, AD 2HJ has remained in the cautious zone since 2017, although the health score of 5 occurring from 2021 to 2024 is higher than the level of 4 achieved during 2017–2020 and suggests improvements may be occurring in the population in that AD. Since 2018, rapid improvements in predicted and realized CPUE have occurred in ADs 3K, 3LNO, and 3Ps, and each AD has sustained *pCPUE* in the healthy zone since 2020. In AD 3Ps, fishery CPUE tripled from 5.8 kg/trap in 2018 to 19.0 kg/trap in 2022. Moreover, predicted fishery discard levels were at or near historical lows or below healthy levels in each of these three ADs in 2017–2018 but have been sustained either in the healthy zone or near time-series lows in each AD since, with the exception of AD 3LNO in 2023 which was predicted to be at a cautious level.

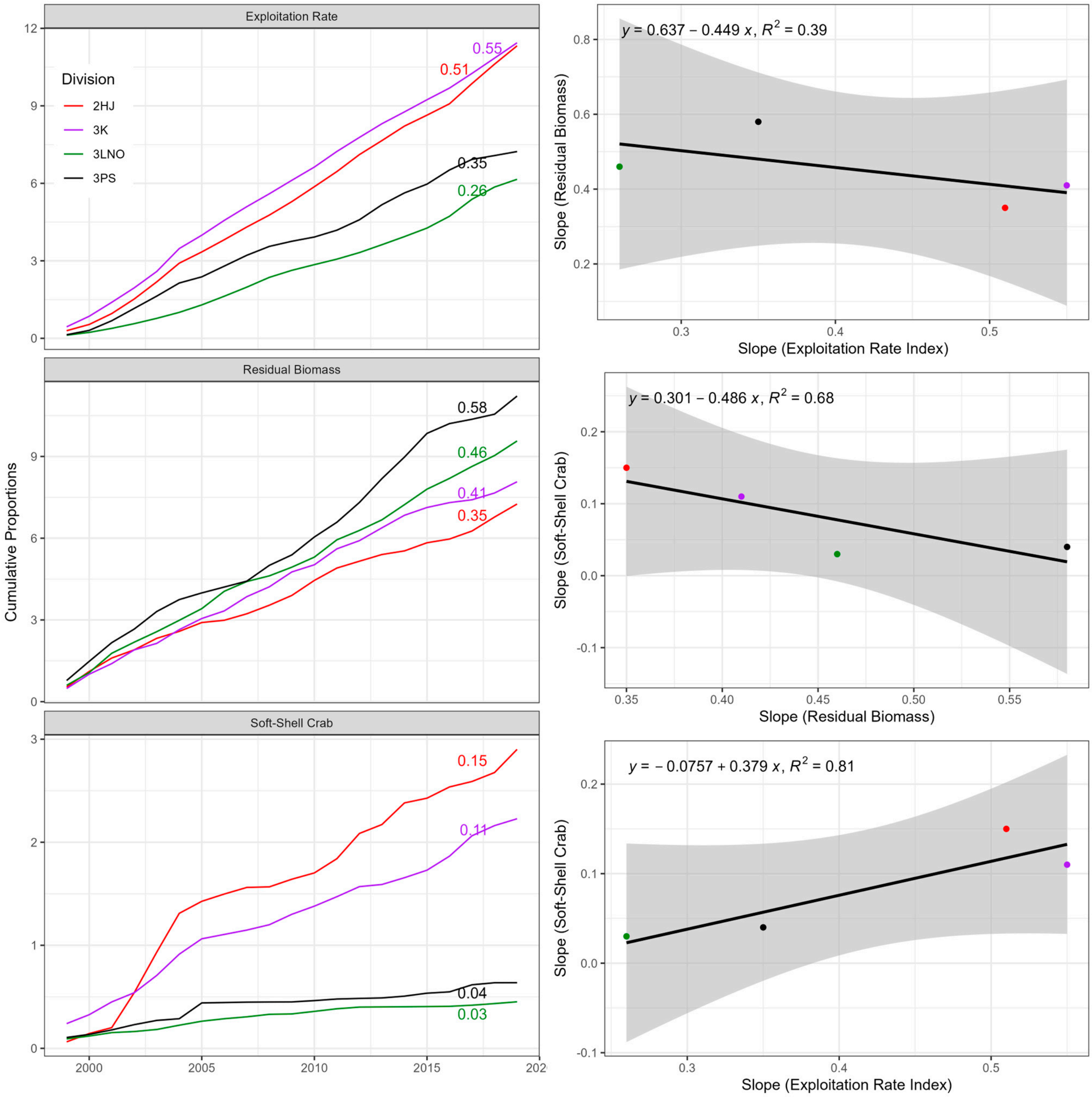

Figure 4. Left panels show cumulative proportions of annual exploitation rate indices (**top row**), residual biomass proportions (**middle row**), and soft-shell crab incidence (**bottom row**) by AD from 1999 to 2019. Numbers show slopes of linear regression models fit through the origins for each metric by AD. **Right panels** show linear regression models fit to scatter plots with point data represented by slopes of cumulative proportions linear regressions for each metric and AD.

The overall abrupt improvements in ADs 3K, 3LNO, and 3Ps stock status are associated with low ERIs in recent years, while the more gradual improvements in AD 2HJ are associated with a more gradual decline in ERIs (Figure 4). In AD 2HJ, *pDIS* has been gradually decreasing in recent years and was below 20% in 2023, while *pCPUE* had remained at about 7.5 kg/trap during 2015–2021, but the rate of improvements in predictions has increased in the past two years. Under status-quo removals in 2024, AD 2HJ discards would be predicted to be in the healthy zone, while under low-moderate ERI (i.e., <20%), *pCPUE* would enter the healthy zone for the first time in sixteen years.

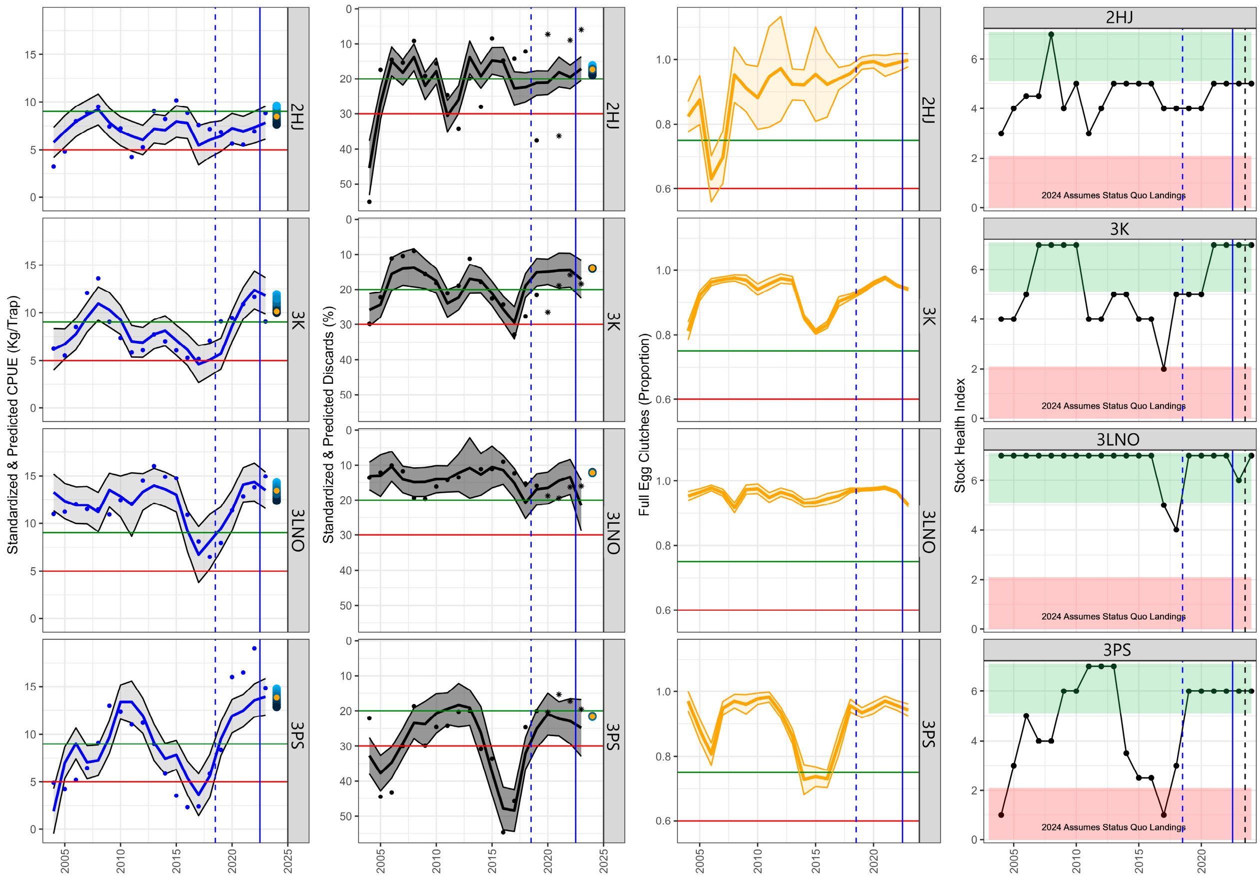

Figure 5. Precautionary Approach framework for NL snow crab. Rows represent ADs. **Left panels** show the *pCPUE* metric, with points showing response data (standardized CPUE), solid lines showing predicted values, and shaded bands showing 95% confidence intervals. **Left-middle panels** show the *pDIS* metric, with points showing response data (standardized discards), solid lines showing predicted values, and shaded bands showing 95% confidence intervals. **Right-middle panels** show proportions of females carrying full clutches of viable eggs, with lines showing index and shaded bands showing 95% confidence intervals. **Right panels** show integrated stock health scores in the context of healthy (green), cautious (white), and critical (red) zones. Orange dots in 2024 in pCPUE (**left**) and pDIS (**middle-left**) metrics show predicted values under status quo landings with 2023, with vertical dots showing predictions under a range of 5% (light blue) to 40% (dark blue) ERI levels. The year 2024 values in integrated stock health score (**right**) panels show predictions under status quo landings with 2023. Horizontal solid lines on *pCPUE*, *pDIS*, and *EGG* panels show reference points differentiating stock status zones, with a critical zone below the red line, a cautious zone between red and green lines, and a healthy zone above the green line. Critical, cautious, and healthy zones in the overall stock health plot (**right panels**) are shown as red, white, and green shaded bands. Vertical lines show the Informal PA Period (dashed blue) and Formal PA Period (solid blue).

Egg clutch fullness levels cannot be as cleanly ascribed to events associated with PA development and implementation, with long-term progressive increases in trend improvement in AD 2HJ and recoveries from low levels occurring in ADs 3K and 3Ps prior to 2018. However, all ADs have coincidentally maintained very high (> 0.9) proportions of mature females carrying full clutches of viable eggs since the Informal PA Period, with no other period in the time series sustaining consistency in this performance metric across all ADs for this long (5 years).

A comparison of long-term trends in mat50 in males across ADs suggests fluctuations reaching levels as low as about 80 or 85 mm CW are a normal feature in the stock populations in these ADs (Figure 6). However, the abrupt decrease to levels of about 65–70 mm

CW from 2015 to 2019 in AD 2HJ was unusual. There have been improvements since 2019 to annual levels of about 75–80 mm CW, suggesting declining ERIs may be beneficial, but the concerning phenomenon persists. In AD 3K, the reversal of a prolonged decrease in the metric from 2005 to 2018 is coincidental with PA development, while high levels of mat50 (>90 mm CW) have been maintained in ADs 3LNO and 3Ps since the Informal PA Period.

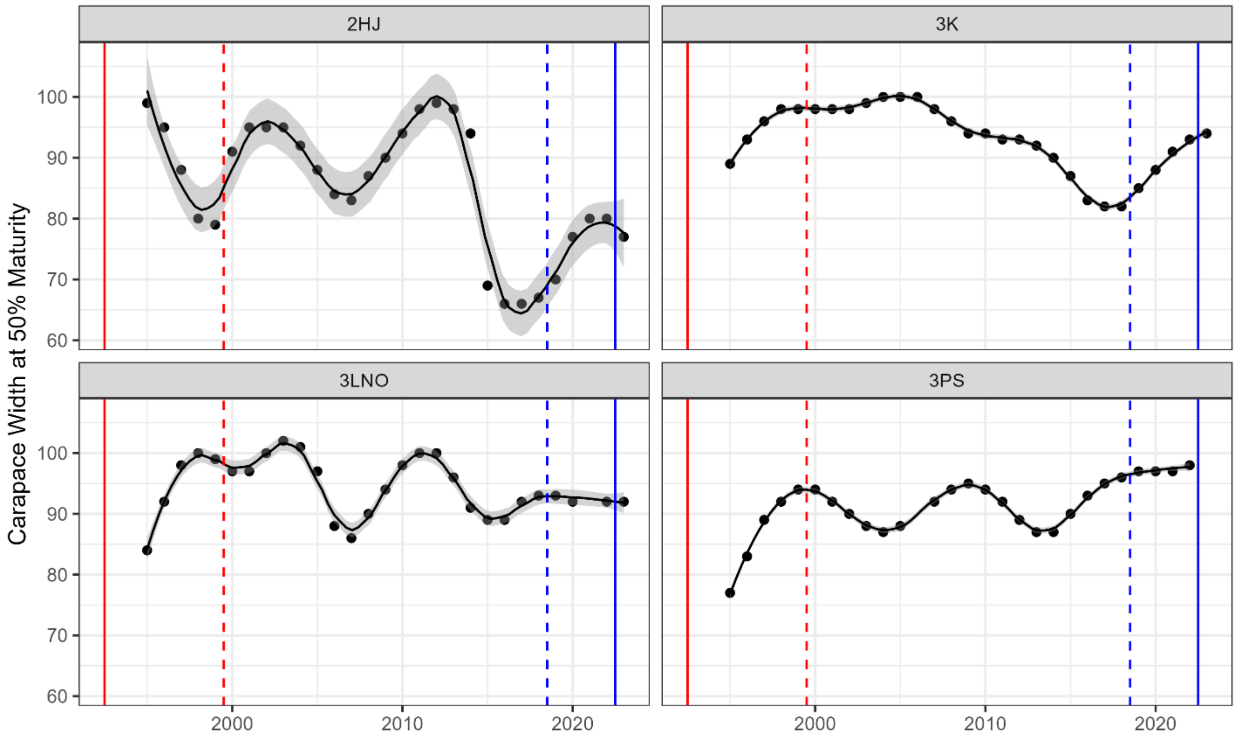

Figure 6. Carapace widths at which 50% of males are predicted to mature (terminally-molted) by year within each AD. Loess regression lines fit the time series point estimates in each AD. Vertical lines show the starts of the groundfish moratorium (solid red), Rationalization Period (dashed red), Informal PA Period (dashed blue), and Formal PA Period (solid blue).

4. Discussion

4.1. PA Management System Timing

The development of a multi-indicator PA management system for NL snow crab and the associated invocation of Informal PA management beginning after 2018 occurred at a pivotal time for the NL snow crab resource. The EBI was at historical lows, and fishery ERIs were enabled to elevate to historical highs. By most operationalized definitions of stock collapse, at just 9% of its historical maximum in 2016, this stock would be classified as collapsed preceding informal PA implementation. However, given that severe depletion had not occurred for multiple decades and that some recovery potential was evident [32], the poor state of resource in the late 2010s did not constitute a collapse according to standardized criteria [47]. Nonetheless, the interpretation of exploitation rates highlights that resource conservation was not the principal priority in the late 2010s while the stock was in a vulnerable state [48]. Accordingly, the pivotal informal change in management strategy for the resource after 2018 is best contextualized as occurring at a sensitive time, and outcomes of the application of PA philosophy into resource management are best judged by the extent to which they helped enable recovery in the context of resource state and ecosystem carrying capacity.

4.2. PA Management System Impacts

Exploitable biomass levels in NL snow crab are strongly affected by both climate and fishing. There is strong climatic control of resource productivity through mechanisms such as water temperature, atmospheric forcing, and sea ice [46]. Despite warm conditions helping promote large individual size, overall, cold conditions are most favorable for sustained high productivity of this cold water specialist [49,50]. NL snow crab are predominately 9–11 years old when they reach legal size, with crab in the exploitable biomass typically 9–13 years of age [44]. Thus, positive impacts of cold conditions during early ontogeny can become evident at lags of a decade or more, and the mid-life benefits of cold conditions can exacerbate realized outcomes [46]. As an extension of this, climate forcings along the NL marine shelf tend to oscillate at roughly decadal time scales [51]; thus, oscillating patterns in resource trajectory can be predictable using long- and mid-term ontogenetic climate variables, such as occurred preceding the forecasted mid-late 2010s decline [11,12]. However, top-down fishing effects are also important in regulating the exploitable biomass, as became particularly obvious during the unusually heavy exploitation period of the mid-2010s, with the downward shift in male SaM indicative of biological harm through fishing [13], an important novel observation on the global scale.

One important aspect of PA fishery management is that it imposes explicit maximum limits on exploitation rates. This represents an important departure from harvest strategies immediately preceding 2019 as the fishery transitioned from a mature state into a senescent state. For example, during 2016–2018, the overall ERIs were 43%, 62%, and 52% annually, the highest levels ever enabled on the stock and beyond those consciously applied to any other known major snow crab stock on a regular basis. Most indicators examined herein suggest that stricter limits on ERIs abruptly invoked in the Informal PA Period, which were near historical lows in all but AD 2HJ, led to improvements beyond what would have been anticipated if exploitation rates had been enabled to remain higher. For example, most AD-specific and overall fisheries CPUE were at levels approximating historical highs and not seen since the EBI was at a level of double or more of what it was in recent years (i.e., 1996–2001). As an extension of this, discard rates in the fishery have become coincidentally low everywhere, and the stock-level residual biomass has been at or near historically high proportions in 2022 and 2023.

In conjunction with the Informal PA Period, the NL snow crab fishery has become overall more efficient in resource extraction than it has been for virtually all of its post-Expansion Period history, with recent broad-scale consistency in minimization of wastage and increased survival of recruits. This outcome is at least partially attributable to the informal implementation of the PA management system. Ancillary supporting indicators of coincidental improvements associated with the shift in management philosophy in 2019 are the development of the longest sustained period of broad-scale high (>90% full clutches) fecundity rates in females seen to date and reversal of a SaM decline in males in AD 3K. Both phenomena have been sustained since the onset of the Informal PA Period. As per its intent, the available evidence shows that the multi-indicator PA management system benefits multiple stock health and fishery performance indicators. Moreover, contrast across ADs reinforces the benefits of invoking this multi-indicator PA management system, with positive changes being realized abruptly and substantially in all ADs where ERIs were immediately curtailed (3K, 3LNO, 3Ps) versus AD 2HJ, where stock improvements have been more gradual in association with gradual reductions in ERI after 2018.

Overall, the suite of circumstantial evidence suggests that this new management approach has equaled or exceeded historical fishery and resource performance outcomes during periods of similar conditions. There appear to be few biological deterrents associated with the adoption of this multi-indicator PA management system into resource use decision-making, particularly when considering performance indicators at the broad stock level. Historically, management strategies for the stock have differed across ADs, generally characterized by higher exploitation rates in the northern ADs than in the southern ADs. However, in the Formal PA Period, all ADs will become more consistent in management strategies due to analogous fishery and resource performance indicators and formalized HCRs. History has shown that the lower exploitation rate strategy in the southern ADs is more effective from both biological protection and fishing efficiency perspectives. The shift to aligning future management strategies in the northern ADs to become more analogous to historical practices in the southern ADs is likely to be of broad benefit to the entire stock, with AD 2HJ representing the most upstream extent of the NL snow crab stock range and prevailing ocean currents flowing south. Accordingly, better protection of the upstream stock components should help safeguard reproductive capacity in downstream ADs with southerly flowing larval drift. Ultimately, homogenous management across the entire stock range reduces the risks of fracturing biological connectivity by exploiting sub-stock components too aggressively.

4.3. Management and Industry Responses

A fundamental difference between the NL snow crab PA framework and those used in other major snow crab stocks, including the southern Gulf of St. Lawrence (sGSL) [31] and the Bering Sea of Alaska [52], is that it promotes increased flexibility for management or industry to fish at levels lower than prescribed by rigid HCRs. This is enabled through the use of HCR ranges rather than explicit levels that scale to biomass. In this regard, HCR ranges create increased room for other factors beyond biomass to feature in decision-making. Interestingly, since the Informal PA system began, all but AD 2HJ have fished at exploitation rates well below what is allowed as the maximum level for the Healthy Zone (42%), generally ranging from about 25–30% per year. This outcome reflects group-level conscious choices, as quotas are set based on co-management principles, invoking industry inputs into decision-making [10]. The exact reasons for this approach are unknown, but it is associated with a global market glut and poor prices for snow crab in recent years, thus likely partially reflecting economic factors. It is also possible that the inclusion of factors other than exploitable biomass into stock health scoring influences harvester and management decision-making. For example, we have heard feedback of increased concerns over discarding and increased efforts by harvesters to minimize discarding in the fishery so as not to dampen the PA stock health score. Similarly, we have received positive feedback regarding the increased use of spatially randomized small-mesh traps in collaborative surveys in recent years because of improved capacity to measure the abundance of females and, thereby, egg clutch health in the stock, indicative of increased buy-in to measure and integrate information on stock components beyond exploitable crab into the decision-making framework in the management system.

Whatever the reasons for the outcome of fishing below maximum allowable limits in most NL snow crab ADs since the Informal PA Period began, the results of this analysis are depicting the approach has had rapid and strong positive results on all analyzed stock status metrics across the majority of the stock range. In contrast, in the adjacent sGSL stock, a more conventional univariate biomass-based PA system is used [31], with the Healthy Zone covering about 60% of the range of historical observations of stock exploitable biomass and an explicit sloping HCR applied, which ranges about 32–45% annual harvest of the exploitable biomass. Under this system, the exploitation rate over the 2010–2022 period averaged 36%, and the residual biomass has decreased from an initial high level (3–54%) during 2010–2011 to a prolonged low level averaging 24% of the exploitable biomass during 2016–2022, with survival rates in the exploitable biomass consistently declining since the PA management system was invoked [53]. Contrasts across the two PA systems suggest that enabling harvest rates below maximum tolerable limits has resulted in a more conservative approach in the NL fishery. However, there is no guarantee that this conservative response by management and industry will continue to be adopted in the event of a resource decline.

4.4. Looking Forward

The informal invocation of the multi-indicator PA management was well-timed to help the NL snow crab stock recover from a historically poor state in the late 2010s, with evidence suggesting it has helped promote fishery extraction that is more efficient than occurred for most of the post-expansion period. Increased extraction efficiency helps foster increased sustainability in fisheries management and is advantageous in a scenario of a resource decline. In this regard, it is important to highlight that a decline in the EBI is anticipated in the short term, with the most recent assessment showing declines in pre-recruit crab [33] and a long-term prognosis for reduced habitat as greenhouse effect warming ensues [46].

This multi-indicator PA system cannot stop a resource decline, but there are measures in place to prohibit excessive exploitation, such as those that occurred under reduced biomass in the late 2010s, if and when the resource does decline. Historical data shows that by keeping ERIs low, sufficient intraspecific competition should be maintained in the population to help safeguard against deleterious outcomes exacerbated by overfishing during periods of naturally dampened population density. In particular, under the assumption that resource status will fall into cautious or even critical zones at some point in the future, the system assures that ERIs will be maintained at levels historically shown to maintain a relatively strong residual biomass in the population and minimize discards in the fishery. The direct incorporation of additional metrics of discards and female fecundity into stock health scoring provides the additional ability to react to factors other than fishing rates that may become problematic during reduced biomass conditions. Any offsetting gains realized through maximizing fishing efficiency during a resource decline are also advantageous from an economic sense as they help keep fishery CPUE high and thus reduce costs associated with effort inputs. Finally, the continued ability of the multi-indicator PA management system to accurately predict fishery outcomes during resource declines should be an asset to help harvesters and managers plan for necessary adjustments. Conceptually, the use of both survey biomass and climate variables to predict fishery outcomes should help bolster the ability of the system to maintain accurate predictions.

It is recognized that this PA management system has not yet been truly tested during a major resource decline. The evidence shown herein suggests it has promoted better than historical stock and fishery performance relative to periods of similar conditions (i.e., moderate exploitable biomass levels) in the past. The ability to continue to promote better than historical stock and fishery performance under low exploitable biomass conditions similar to recent historic lows, if they occur, will be indicative of its ability to promote sustainable fishing in the long run.

5. Synopsis

Our analysis shows that similar to all male-only crab fisheries, exploitation strategies of NL snow crab must adjust to stock size changes as they occur. Recent history from this fishery demonstrates problems resulting from overfishing, and the contrast of historical practices across ADs demonstrates the biological and fishery benefits of consistently applying low-moderate exploitation rates. The NL snow crab fishery teaches us that male-only harvest strategies alone are not sufficient for resource management of this or other male-only crab fisheries without conservation-oriented limits on fisheries exploitation rates. Leading inferences from outcomes on the invocation of a multi-indicator PA management system for this vital marine resource suggest that the achievement of additional beneficial outcomes stemming from maximizing extraction efficiency are indeed achievable ancillary goals for resource management in male-only crab fisheries.

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