Stock assessment and evaluation for North Pacific stock of snow crab (fiscal year 2021)

Japan Fisheries Research and Education Agency

Fisheries Stock Assessment Center, Fisheries Resources Institute

Participating Organizations:

Aomori Prefectural Industrial Technology Research Center Fisheries Institute, Iwate Prefectural Fisheries Technology Center, Miyagi Prefectural Fisheries Technology Center, Fukushima Fisheries Resources Institute, Fukushima Prefectural Fisheries and Marine Science Research Center, and Ibaraki Prefectural Fisheries Experiment Station

Summary

The abundance of this stock was estimated using the just another state-space stock assessment model (JASAM) for standing stock size obtained from bottom-trawl surveys. The total stock abundance of males and females has been declining since the 2008 fishing season (1,330 tons), and was estimated to be 237 tons in the 2020 fishing season, the lowest since surveys began in 1997. Spawning stock biomass of female crabs after the end of the fishing season (hereinafter referred to as "SSB") also showed a declining trend during the survey period, and was estimated to be a record low of 55 tons in the 2020 fishing season. The abundance of this stock has continued to decline since the Great East Japan Earthquake in 2011 (hereinafter referred to as "the Earthquake"), despite the fact that fishing pressure has remained at a very low level.

In the Research Agency Forum on Reference Points held in April 2020, a hockey-stick model was applied to the stock-recruitment relationship of this stock. The natural mortality coefficient (M) of this stock is rising, and assuming that the M of the previous 3 years will continue, it was judged to be difficult for the stock to be maintained sustainably even if the catch is set to zero in the applied stock-recruitment relationship. Therefore, the proposal for SBmsy, the reference SSB required for MSY (maximum sustainable yield), for this stock was postponed. In March 2021, the Stock Management Policy Commission and the Fishery Policy Council set the stock management target for this stock at the abundance levels of 2019 (436 tons in the 2020 stock assessment).

The results of this year's assessment showed that stock abundance in 2019 was revised downward from 436 tons to 316 tons, but stock abundance in the 2020 fishing season was the lowest since surveys began (237 tons), meaning that stock abundance was lower than the level of 2019, which was the target set in stock management basic policy. Based on trends seen in the previous 5 years (2016 to 2020 fishing seasons), the SSB is judged to be in a "Decrease" trend. The catch strategy for this stock is to "avoid operations which deliberately catch this stock", and the total allowable catch is calculated to be 20 tons based on the maximum catch in weight since 2011, when the Earthquake occurred. The forecasted stock abundance for the 2022 fishing season and the calculated catch in weight based on current fishing pressure are calculated to be 174 tons and 3.3 tons, respectively.

Item	Value	Description
Reference points & MSY values		
SBtarget	—	SSB required for MSY (SBmsy)
SBlimit	—	SSB required for catch of 60% of MSY (SB0.6msy).
SBban	—	SSB required for catch of 10% of MSY (SB0.1msy).
Fmsy	—	
%SPR (Fmsy)	—	
MSY	—	
SSB and fishing pressure in the 2020 fishing season		
SB2020	55 tons	SSB in 2020 fishing season
F2020	Fishing pressure in 2020 fishing season (fishing coefficient F) (Male (immature), Male (mature), Female) = (0.05, 0.05, 0.01)	
%SPR (F2020)	96.8%	%SPR in 2020 fishing season %SPR corresponding to M = 0.698 (2020 fishing season)
%SPR (F2018-2020)	96.0%	%SPR corresponding to current fishing pressure (2018 to 2020 fishing seasons)
Ratio of levels required for target reference points to levels required for MSY		
SB2020 / SBtarget (SBmsy)	—	Ratio of target reference points (SSB required for MSY) to SSB in 2020 fishing season
F2020 / Fmsy	—	Ratio of fishing pressure required for MSY to fishing pressure in 2020 fishing season*

*Ratio calculated based on %SPR converted F, which reflects Fmsy fishing pressure at the selection probability of the 2020 fishing season

Stock-recruitment relationship: hockey-stick model (with autocorrelation)

Level of SSB	—
Level of fishing pressure	—
Trends in SSB	Decrease

This stock could not be represented using a Kobe plot because the levels of SSB required for MSY (SBmsy) were not calculated.

Fishing year	Stock abundance (tons)	SSB (tons)	Catch in weight (tons)	F / Fmsy	Exploitation rate (%)
2017	541	126	12.7	—	2.3
2018	430	97	3.3	—	0.8
2019	316	71	7.4	—	2.3
2020	237	55	7.9	—	3.3
2021	193	44	3.7	—	1.9
2022	174	40	3.3	—	1.9

Stock abundance is the fishable stock, SSB is the post-fishing season SSB, and values for 2021 and 2022 are estimates based on future forecasts.

ABC for the 2022 fishing season (tons)	SSB in 2022 fishing season Forecasted average (tons)	Ratio to current fishing pressure (F/F2018-2020)	Exploitation rate in 2022 fishing season (%)
—	40	—	—

Comments:

- In March 2021, the Stock Management Policy Commission set the total allowable catch based on the maximum catch in weight since 2011, when there were no operations which deliberately caught this stock.
- The average values of the 2018 to 2020 fishing seasons (F2018-2020) were used for current fishing pressure.
- In this stock, the natural mortality coefficient M is high, and stock abundance will continue to decline even if catch is set to zero in the applied HS model for stock-recruitment relationship. In addition, stock abundance and SSB are at the lowest levels since surveys began in 1996, and the population must be conserved.

1. Data Sets

The data sets used for this stock assessment are as follows:

Data Sets	Basic Information & Related Surveys
Catch in weight by year	Fishery catch statistics by prefecture (Ministry of Agriculture, Forestry and Fisheries, and prefectural fishery experimental stations) Catch performance report for Bottom-Trawl Fishing in Offshore Waters, North Pacific (Fisheries Agency) Market research (Fukushima Prefecture)
Stock abundance index Recruitment indices	Bottom-Trawl Survey (October to November, Japan Fisheries Research and Education Agency)
Age of maturity Average weight by year	Bottom-Trawl Survey (October-November, Japan Fisheries Research and Education Agency)

Catch in weight is calculated by fishing year (from July to June of the following year). Fishing season is from December to March of the following year.

2. Ecology

(1) Distribution / Migration

In the North Pacific off Honshu Island, Japan (the North Pacific), snow crabs are distributed at depths of 150 m to 750 m in offshore waters from Aomori to Ibaraki (Fig. 2-1, Kitagawa 2000). In the North Pacific, males with a carapace width of 80 mm or more, and mature females were catch targets. Fishable crabs are distributed mostly at 400 m to 500 m depth, and this depth layer is the primary fishing grounds (Kitagawa 2000). The fishing grounds of the North Pacific is characteristically deeper than those of other area around Japan, a depth of 150 m to 250 m along the Sea of Okhotsk coast (Domon 1965) and a depth of 200 m to 400 m in the Western region of the Sea of Japan (Ito 1956, Kanamaru 1990). Based on results of bottom-trawl survey , the carapace width composition for this species shows that young crabs with a carapace width of 20 mm to 40 mm live across a wide area at a depth shallower than 400 m , and it is presumed they migrate to deeper waters as they grow (Kitagawa 2000), but the details of life history in the North Pacific stock remain unclear, especially regarding seasonal deep-shallow migration and North-South migration.

(2) Age / Growth

In the North Pacific stock, molt-age is estimated by carapace width. It is estimated that snow crabs in the Sea of Japan molt multiple times within 1 year (6th instar or less) until carapace width is approx. 20 mm, then molt once per year thereafter until their terminal molt (Kuwahara et al. 1995). Individual growth ceases after the terminal molt in both males and females. In this stock, there is no difference in growth between males and females until the 9th instar, with a carapace width of 28 mm to 42 mm by the 8th instar, and 42 mm to 56 mm by the 9th instar (Fig. 2-2, Table 2-1, Ueda et al. 2007).

In males, the carapace width is 56 mm to 74 mm by the 10th instar, some individuals complete their terminal molt at or after this stage. Thereafter, in males which have not completed their terminal molt, the carapace width is 74 mm to 86 mm by the 11th instar, 86 mm to 98 mm by the 12th instar, and most individuals complete their terminal molt by the 13th instar (98 to 110 mm). It is not common, but there are some individuals which do not complete their terminal molt by the 13th instar (carapace width 98 mm or more), but we have not found individuals in the 14th instar with carapace width 110 mm or more which have not yet completed their terminal molt.

In females, individual carapace width is approx. 56 mm to 76 mm by the 10th instar. In this stock, most females are considered to have completed their terminal molt in the 11th instar, so stock assessment for this stock presumes that all females in the 11th instar will have completed their terminal molt. Likewise, if this stock is presumed to have the same growth pattern as the Sea of Japan stock until the 6th instar, then lifespan is considered to be more than 10 years.

(3) Maturation / Spawning

In this stock, some males start their terminal molt in the 10th instar (Fig. 2-2, Ueda et al. 2007). Individual males with a small carapace width that have completed their terminal molt stop its growth of carapace, so males with a carapace width of 80 mm or less that have completed their terminal molt are not fishable stock. In this report, “mature” indicates completion of the terminal molt, so individuals which have not completed their terminal molt were recorded as immature, and individuals which have completed their terminal molt were recorded as mature.

The ratio of maturity by carapace width obtained in bottom-trawl surveys from 1997 to 2020 is shown in Figure 2-3. In males, there were a few mature individuals with a carapace width of 60 mm or less, but more than 50% of mature individuals had a carapace width of 80 mm or more, and most individuals with a carapace width of 110 mm or more were mature. This stock is said to have fewer large males than the Sea of Japan stock, but the reason for this appears to be a difference in size at maturity, not a difference in growth rates (Ueda et al. 2007).

In females, maturity ratio became higher from a carapace width of 60 mm, and was attained more than 50% with a carapace width of 68 mm or more, and most individuals with a carapace width of 76 mm or more were mature. The carapace width of mature females is nearly the same as the Sea of Japan stock. Details about the spawning season and spawning grounds are unclear, but many females with egg clutches that are about to hatch are collected from winter to spring.

(4) Predator-Prey Relationships

The feeding habits in the North Pacific off Tohoku region are unclear, but snow crabs in other oceans primarily feed on benthic organisms, and a variety of other organisms including crustaceans, fish, squid, polychaetes, shellfish, and echinoderms, in addition to some reports of cannibalism (large individuals preying on smaller individuals) (Yasuda 1967, Ogata 1974, Lovrich and Sainte-Marie 1997, Kolts et al. 2013). The foraging season is year-round, and foraging grounds are at depths of 150 to 750 m. Small individuals are preyed upon by Pacific cod, eelpouts, and skates, and there have been some reports of large individuals preyed upon by Pacific cod immediately after molting (Ito et al. 2014, Ito 1968, Robichaud et al. 1991).

(5) Special Remarks

In this stock, the natural mortality coefficient (M) was estimated using JASAM (Shibata et al. 2021, see Appendix 2). Results showed an increase in M in this decade, which accounted for the stock population size recovery failure despite maintaining extremely low levels of fishing pressure since the Earthquake. The reason for the increase in M is unclear, but there are indications of a correlation with the rising of bottom water temperature in the habitat of snow crabs off Tohoku region (Shibata et al. 2021, Appendix 6). In this report, M is the natural mortality coefficient from December 1st of a given year to December 1st of the following year. For example, the natural mortality coefficient from December 1, 1997 to December 1, 1998 is described as "the M for 1997".

3. Fishery Status

(1) Fishery Overview

In this report, catch in weight is aggregated with the fishing year set from July to June of the following year. This stock is primarily caught by offshore bottom-trawl fisheries (hereinafter referred to as "offshore trawlers"), but there are very few dedicated vessels that selectively catch snow crabs, so crabs are usually one catch target handled together with other species of fish. The majority of the catch in weight is caught Southwards of Miyagi Prefecture, using otter trawling (hereinafter referred to as "trawling"). In particular, Fukushima Prefecture accounts for a large percentage of catches (Fig. 3-1). Fukushima began catching snow crabs around 1975 to 1980, and Fukushima vessels have caught the majority of catch in weight of this stock since the mid-1990s (Table 3-1). However, Fukushima vessels have been forced to suspend or restrain operations due to the effects of the Earthquake, and only experimental operations have been conducted since November 2012.

In 1996, Acts issued by the Ministry of Agriculture, Forestry and Fisheries introduced regulations which set the fishing season (from December 10 to March 31 of the following year) and catch size (prohibiting catches of males with a carapace width of 80 mm or less, and immature females). Furthermore, snow crabs were designated as subject to TAC rules when these regulations were introduced. In addition to these official regulations, landing limits and no-operation days have been set per operation of each offshore trawling vessel in Matsukawaura Port in Fukushima, the most major landing port.

(2) Trends in Catch in Weight

Catch in weight by sex has been recorded at Matsukawaura Port in Fukushima since the 1985 fishing season, but catch in weight for the entire region from Aomori to Ibaraki has only been recorded since the 1996 fishing season. Trends in catch in weight for all prefectures show that it reached a record high of 353 tons in the 1995 fishing season, excluding Iwate, then declined to 107 tons by the 2000 fishing season (Fig. 3-1, Table 3-1). In the 2003 fishing season, catch in weight suddenly increased to 279 tons due to increase in Ibaraki, but if this is excluded, then the total catch in weight for all prefectures followed the same trends as catch in weight in Fukushima, which catches the majority of this stock, where catch reached 245 tons in the 2008 fishing season, then declined to 159 tons in the 2010 fishing season.

Catch in weight has remained at low levels since the 2011 fishing season due to suspension of operations by Fukushima vessels following the Earthquake. Catch in weight was 0.5 tons in the 2011 fishing season, 5.6 tons in the 2012 fishing season when experimental operations began, and 12.7 tons in the 2017 fishing season. In the 2018 fishing season, catch declined to 3.3 tons due to reduced effort related to stormy weather, then reached 7.9 tons in the 2020 fishing season. The fishing effort for snow crabs in this region is influenced by the price trends of snow crabs and other commercial fishes, so the annual changes in catch in weight may not have directly reflected actual changes in the stock, even during the pre-Earthquake years with higher catch in weight.

Trends in catch in number by sex and by maturation level show that the catch in number of females is higher than the catch in number of males in most fishing years since data was first collected in the 1997 fishing season (Fig. 3-2).

(3) Fishing Effort

This stock is mainly caught by offshore trawlers. Using the catch performance report for Bottom-Trawl Fishing in Offshore Waters (hereinafter referred to as “Offshore Trawl Report”), fishing effort was estimated based on the number of non-zero catches of snow crabs (total number of nets hauled by fishing vessels on days when snow crabs were caught) of Fukushima offshore trawl vessels, and the trends were investigated (Fig. 3-3).

Fishing effort stayed around 2,000 nets in the 1997 to 2002 fishing seasons, then increased to 3,600 nets in the 2003 fishing season, and dropped to 1,500 nets in the 2005 fishing season. Then, effort increased to 3,600 nets again in the 2008 to 2009 fishing seasons, but it was 0 nets in the 2011 fishing season due to the Earthquake. Only experimental operations have been conducted since the 2012 fishing season, with extremely low effort, reaching a maximum of 56 nets (47 nets in the 2019 fishing season). In addition, effort levels in the 2010 fishing season were not available because data of the Offshore Trawl Report was lost before submission due to the Earthquake. Meanwhile, the operating area in the 2019 fishing season showed significant changes compared to the pre-Earthquake period (2009 fishing season), and only covered some of the fishing grounds in Soma offshore waters (Fig. 3-4).

4. Stock Status

(1) Stock Assessment Methods

Standing stock data (swept-area method, Appendix 3) based on catch in number by instar and by sex (Appendix 5) and the surveys for demersal fish stock abundance conducted by the research vessel Wakatakamaru since 1997 (hereinafter referred to as “bottom-trawl survey”) (Aomori to Ibaraki, offshore waters at depths of 150 to 900 m, 153 total sites in 2020, snow crabs collected at 88 sites) was used for an abundance index. We applied JASAM (just another state-space stock assessment model) (Shibata et al. 2021) which was developed based on SAM (state-space stock assessment model, Nielsen and Berg 2014) and estimated the stock abundance (Appendix 1).

(2) Trends in Abundance Indices

Standing stock data from the bottom-trawl survey showed a long-term increase from the 1997 fishing season (496 tons) to the 2007 fishing season (1,777 tons), followed by trends of decrease (Fig. 4-1, Table 4-1). Stock sizes have fluctuated greatly throughout the survey period, with an increase from 407 tons in the previous season to 992 tons in the 2019 fishing season, then declining to 114 tons in the 2020 fishing season, the lowest since surveys began in 1997. Current SSB (standing stock of mature female individuals) based on survey results from each fishing year has also fluctuated greatly in a similar way to the standing stock, reaching 430 tons in the 1999 fishing season, followed by long-term trends of decrease. In the 2020 fishing season, the current SSB is 18 tons, which together with standing stock levels, is the lowest since the 1997 fishing season.

Using data about non-zero catches and catch in weight from the Offshore Trawl Report, we investigated trends in catch per unit effort (CPUE) in the primary fishing grounds of offshore Fukushima. Results showed that CPUE (kg/net) declined slowly until the 2005 fishing season, then increased slightly in the 2006 to 2008 fishing seasons, but returned to the same levels as 2005 in the 2009 fishing season (Fig. 4-2). CPUE was not calculated for the 2011 fishing season because all operations were suspended, nor for the 2014 fishing season because effort was only 1 net. Excluding the 2014 fishing season, CPUE in the 2012 to 2017 fishing seasons showed trends of rapid increase with values of 55.4, 63.4, 122.0, 162.1, and 187.8 kg/net, but the maximum fishing effort was only 56 nets. CPUE has fluctuated significantly since the 2018 fishing season, with a CPUE of 64.6 kg/net for 20 nets in the 2018 fishing season, and 106.1 kg/net for 47 nets in the 2019 fishing season.

The Offshore Trawl Report records catch in weight and operation sites on an aggregated per-day basis, making it difficult to distinguish between targeted operations and incidental catch. In post-Earthquake years, Fukushima vessels, which previously accounted for the majority of catch, are only conducting experimental operations, resulting in significant changes in both fishing effort and operating area (Fig. 3-4). According to interviews with fishermen, in recent years, operations have been limited to several visits per season to deeper waters (depth of 400 to 500 m), where more broadbanded thornyheads and snow crabs are found. The reasons above lead us to believe that trends in offshore trawl CPUE do not reflect the fluctuation in stock abundance.

(3) Trends in Stock Abundance and Fishing Pressure

The total stock abundance of males and females estimated using JASAM fluctuated between 721 and 1,330 tons during the 1997 to 2008 fishing seasons, then shifted to a declining trend, with stock abundance reachingthe lowest of 237 tons in the 2020 fishing season (Fig. 4-3, Table 4-1). Both male and female stocks peaked in the 2008 fishing season (females: 524 tons, males: 806 tons) followed by a declining trend (Fig. 4-4). Prior to the 2002 fishing season, males and females showed different trends, but in recent years males and females are showing similar trends, with fishable stock in 2020 of 111 tons for females, and 125 tons for males. Trends in SSB after the 1998 fishing season (416 tons) show a long-term declining trend throughout the survey period (Fig. 4-5). There was a slow increase in the 2003 to 2007 fishing seasons, followed by a declining trend, reaching the lowest of 55 tons in the 2020 fishing season.

The natural mortality coefficient (M) was estimated to be M = 0.191 in 1997, followed by a consistent increasing trend (Fig. 4-6, Table 4-2). The estimate was M = 0.698 in 2020, with an average value of M = 0.677 in the previous 3 years.

The total exploitation rate for males and females peaked at 30.6% in the 1997 fishing season, then declined to 12.4% by the 2000 fishing season, and increased to 37.3% in 2003 (Fig. 4-7, Table 4-1). Afterwards, it remained around 13 to 18% during the 2004 to 2010 fishing seasons. In the 2011 fishing season, operations were suspended for Fukushima vessels due to the effects of the Earthquake, resulting in a negligible catch in weight, while the exploitation rate plummeted to only 0.1%. Although Fukushima vessels began experimental operations in the 2012 fishing season, the exploitation rate has remained very low at 0.1 to 3.3% since the 2012 fishing season (3.3% in the 2020 fishing season). Likewise, F values have remained low since the Earthquake. Since the 2012 fishing season, F values have only been 0.001 to 0.034 (total value for males and females, 0.034 in the 2020 fishing season) (Fig. 4-8).

Trends in recruitment and recruitment per spawning (RPS) are shown in Figure 4-9. In this graph, recruitment is the population size of females in the 8th instar, estimated using JASAM. The RPS and recruitment increased among the 2002 to 2008 year classes, reaching 31.2 ind./kg in the 2008 year class. Afterwards, levels have been fluctuating, but there is a long-term declining trend, remaining at a low value of 12.0 ind./kg among the 2020 year class.

In this stock assessment method, each parameter has been re-estimated with updated data, including the natural mortality coefficient M, to update values for stock abundance. In order to confirm changes in estimated M values after the data update, we performed a retrospective analysis by removing one year of data at a time, starting from the most recent year (Supplementary Figure 2-6). Comparing the results of the previous 3 years showed that estimated M values up to 2018 (estimated M for 1997 to 2018 based on data from 1997 to 2018, the same applies below) and 2019 both reached a maximum in 2012, then leveled off or showed a slow declining trend. However, the estimated value of M up to 2020 in this report has been rising, and despite shifting to a slower rate of increase after 2012, M continued to rise, and reached 0.698 in 2020, a record high since 1997.

M in this stock was estimated based on standing stock sizes from bottom-trawl surveys, with trends in standing stock in the 2018 to 2020 fishing seasons showing a large increase between the 2018 to 2019 fishing seasons, followed by a large decrease between the 2019 to 2020 fishing seasons (Fig. 4-1). Standing stock has fluctuated while fishing pressure has remained low, which leads us to believe that estimates for M up to 2019 were low compared to M up to 2018, and that estimates for M up to 2020 were relatively high compared to M up to 2019.

In the 2020 stock assessment, stock abundance was estimated to be 436 tons in 2019, but this was corrected to 316 tons after M was revised higher in the 2021 stock assessment. However, stock abundance in the 2020 fishing season was the lowest since surveys began (237 tons), meaning that stock abundance was lower than the level of 2019, which was the target set in stock management basic policy (estimated stock assessment in 2020 was 436 tons, which was revised to 316 tons in this report).

Item	Value	Description
SB2020	55 tons	SSB in 2020 fishing season
F2020	Fishing pressure in 2020 fishing season (fishing coefficient F) (Male (immature), Male (mature), Female) = (0.05, 0.05, 0.01)	
U2020	3.3%	Exploitation rate in 2020 fishing season

(4) Yield Per Recruit (YPR), Spawning Per Recruit (SPR), and Current Fishing Pressure

Yield per recruit (YPR) and spawning per recruit (SPR) were used to investigate the current fishing pressure and annual changes in fishing pressure. Spawning per recruit (SPR) was assessed by comparing the SPR ratio (%SPR) with and without fishing pressure (Fig. 4-10).

The %SPR and YPR of this stock were calculated for each sex using an instar composition model which incorporate the terminal molt of snow crabs (Ueda et al. 2009) (Fig. 4-10). Estimated values obtained through JASAM were used for M and terminal molt rate. In this stock, males with a carapace width of 80 mm or more and mature females are fishable, but we assumed that non-fishable stock was caught with the same F as fishable stock, then released after capture. Please note that calculations were made without consideration of biological lifespan, and we assumed that 50% of non-fishable stock survived after release.

If M is set at the average value for the previous 3 years (M = 0.677), then Fmax is estimated to be 0.36 for males and 0.28 for females, and F0.1 is 0.27 for males and 0.21 for females, and F30%SPR is 0.56 for females. In addition, F2018-2020 (average for the 2018 to 2020 fishing seasons) is 0.025 for males and 0.016 for females, which is extremely low when compared to F0.1 and other values. However, average fishing pressure before the Earthquake (F2006-2009, excluding the 2008 fishing season) was 0.13 for males and 0.24 for females, which is greater than F0.1 for females.

On the other hand, we calculated %SPR for females based on the F value for females by year and M by year in the 1997 to 2019 fishing seasons, estimated from JASAM (Fig. 4-11). Although the %SPR fluctuated between 25 and 50% until the 2010 fishing season, it rose to over 95% after the 2011 fishing season due to extreme reduction in fishing pressure after the Earthquake, and was 96.8% in the 2020 fishing season.

Item	Value	Description
%SPR (F2020)	96.8%	%SPR in 2020 fishing season
%SPR (F2018-2020)	96.0%	%SPR corresponding to current fishing pressure (2018 to 2020 fishing seasons)

(5) Stock-Recruitment Relationship

The relationship (stock-recruitment relationship) between SSB (in weight) and recruitment (in number) is shown in Figure 4-12. In this stock, SSB is the stock abundance of mature female individuals (11th instar) after the fishing season ends, and recruitment is the stock population size of crabs in the 8th instar (assumed 5 years old). In the Research Agency Forum on Reference Points held in April 2020, a hockey-stick model was applied for stock-recruitment relationships of this stock (Morikawa et al. 2020). The data used to estimate the parameters of the stock-recruitment relationship model was SSB and recruitment based on stock assessments for 2019 (Shibata et al. 2020), and the optimization method was the least squares method, and autocorrelation was considered regarding residuals in recruitment. However, because the process of recruitment is unknown for this stock, our estimates assume a 5-year recruitment period similar to the Sea of Japan stock. Please note that in the JASAM calculations used to estimate stock abundance, the recruitment of individuals in the 8th instar was given a different assumption for reproduction, in a random walk pattern. In addition, due to the need for consideration of many factors including selection of a model for incorporating stock-recruitment relationship in JASAM, stock-recruitment relationship for this stock were not included in our JASAM calculations. For example, estimates for stock-recruitment relationship were processed using a method other than JASAM (Morikawa et al. 2020). However, we will continue to collect information through surveys and experiments, and we will consider the inclusion of stock-recruitment relationship in JASAM as a challenge to tackle in the future.

Stock-recruitment relationship model	Optimization method	Autocorrelation	a	b	S.D.	ρ
Hockey-stick model	Least squares method	Yes	18.169	259.85	0.275	0.861

In this table, a is the slope of the reproduction curve (ind./kg) up to the HS breakpoint, and b is SSB (tons) at the breakpoint.

(6) Levels and Reference Points Required for MSY Under Current Environmental Conditions

In the Research Agency Forum on Reference Points previously mentioned, a reference point plan required for sustainable maintenance of stock was not proposed due to the revelation that if current M continues in this stock in the future, then stock abundance will continue to decline even if catch is set to zero in the applied HS model for stock-recruitment relationship.

Item	Value	Description
SBtarget	—	A target reference point. SSB required for MSY (SBmsy).
SBlimit	—	A limit reference point. SSB required for catch of 60% of MSY (SB0.6msy).
SBban	—	Level for fishing ban. SSB required for catch of 10% of MSY (SB0.1msy).
Fmsy	—	
%SPR (Fmsy)	—	%SPR corresponding to Fmsy
MSY	—	Maximum Sustainable Yield

(7) Stock Levels/Trends and Fishing Pressure Levels

In this stock, M in recent years estimated by JASAM is high, and stock abundance will continue to decline even if there is no fishing in the applied stock-recruitment relationship model, so we could not calculate SSB or fishing pressure required for MSY. Therefore, we did not propose target reference points (SBmsy), so a Kobe plot based on those reference points could not be created, and stock levels based on MSY levels could not be determined. Stock abundance in the 2020 fishing season estimated by JASAM was the lowest since surveys began in 1997 (237 tons), meaning that stock abundance was lower than the level of 2019, which was the target set in stock management basic policy (estimated stock assessment in 2020 was 436 tons, which was revised to 316 tons in this report). Based on trends seen in the previous 5 years (2016 to 2020 fishing seasons), the SSB is judged to be in a “Decrease” trend.

Item	Value	Description
SB2020 / SBmsy (SBtarget)	—	Ratio of SSB required for MSY (target reference points) to SSB in 2020 fishing season
F2020 / Fmsy	—	Ratio of fishing pressure required for MSY to fishing pressure in 2020 fishing season*

*Ratio calculated based on %SPR converted F, which reflects Fmsy fishing pressure at the selection probability of the 2020 fishing season

Level of SSB	—
Level of fishing pressure	—
Trends in SSB	Decrease

5. Future Forecast

(1) Setting Future Forecasts

Future forecast calculations were performed for the 2021 to 2052 fishing seasons based on stock abundance by instar in the 2020 fishing season estimated in stock assessment reports (Appendix 2). Recruitment (8th instar) in future forecasts was predicted based on SSB in each annual fishing season using the HS model for stock-recruitment relationship proposed by Morikawa et al. (2020). Calculations were repeated 5,000 times assuming errors which follow log-normal distribution to account for uncertainty in recruitment. Stock abundance after the 2021 fishing season was calculated based on forecasted stock abundance (weight of catch targets, specifically males with a carapace width of 80 mm or more and mature females) and current fishing pressure (F2018-2020), using the current M (average value in 2018 to 2020) as the survival rate after the 8th instar. For reference, calculations were also performed with fishing pressure set to zero after the 2022 fishing season.

(2) Harvest Control Rules

Harvest Control Rule drafts are catch strategy proposals which aim for better results than the target reference point plans in consideration of the probability of success for both maintenance and recovery of SSB, which set fishing pressure (F) and other factors that correspond to SSB. However, in the Research Agency Forum on Reference Points, a reference point plan was not proposed and also

Harvest Control Rule draft for this stock.

(3) Forecasts and ABC Calculation for the 2022 Fishing Season

The Stock Management Policy Commission and the Fishery Policy Council perform calculations and set the total allowable catch for this stock with consideration of the maximum catch in weight since 2011, when there were no operations which deliberately caught this stock. In other words, because there are no proposed target reference points, the current situation does not allow for ABC to be calculated using estimated results for stock abundance or catch strategy. For reference, forecasted catch in weight was calculated based on the forecasted stock abundance for 2022 and current fishing pressure. The forecast results for the 2022 fishing season are a catch in weight of 3.3 tons, and an average SSB of 40 tons.

ABC for the 2022 fishing season (tons)	SSB in 2022 fishing season Forecasted average (tons)	Ratio to current fishing pressure (F/F2018-2020)	Exploitation rate in 2022 fishing season (%)
—	40	—	—

Comments:

・ In March 2021, the Stock Management Policy Commission set the total allowable catch based on the maximum catch in weight since 2011, when there were no operations which deliberately caught this stock.

・ The average values of the 2018 to 2020 fishing seasons (F2018-2020) were used for current fishing pressure.

・ In this stock, the natural mortality coefficient M is high, and stock abundance will continue to decline even if catch is set to zero in the applied HS model for stock-recruitment relationship. In addition, stock abundance and SSB are at the lowest levels since surveys began, and the population must be conserved.

(4) Forecast for the 2023 Fishing Season and After

The results of future forecasts, including those for 2023 and after, are shown in Figure 5-1 and Table 5-1. If the current fishing pressure in operations continues for 10 years, then the forecast for SSB in the 2032 fishing season is an average of 10 tons (80% prediction interval of 5.3 to 16.2 tons). On the other hand, even if catch is set to zero, stock abundance will continue to decrease, and the forecast for SSB in the 2032 fishing season is an average of 11 tons (80% prediction interval of 5.5 to 17.3 tons).

Uncertainty under consideration: Recruitment					
Item	SSB in the 2032 fishing season	80% Prediction interval	Probability (%) that SSB will exceed the reference points below in the 2032 fishing season		
	(tons)	(thousand tons)	SBtarget	SBlimit	SBban
F2018-2020	10	5.3 - 16.2	—	—	—
[Reference] F = 0	11	5.5 - 17.3	—	—	—

6. Summary of Stock Assessment

Stock abundance of this stock peaked at 1,330 tons in the 2008 fishing season, followed by a declining trend, and stock abundance reached the lowest of 237 tons in the 2020 fishing season. In the Research Agency Forum on Reference Points held in April 2020, an HS model was applied for stock-recruitment relationship of this stock, and if natural mortality coefficient (M) of this stock of the previous 3 years continues in the future, it is judged that it will be difficult for the stock to be maintained sustainably even if the catch is set to zero. Therefore, the SSB required for MSY (SBmsy) in this stock couldn't be calculated. Stock abundance in the 2020 fishing season was the lowest since surveys began in 1997, meaning that stock abundance was lower than the level of 2019, which was the target set in stock management basic policy. Based on trends seen in the previous 5 years (2016 to 2020 fishing seasons), the SSB is judged to be in a "Decrease" trend.

7. Additional Comments

A "reference point level setting plan" was presented at the Research Agency Forum on Reference Points held in April 2020, which sets the levels for reference points if M decreases in the future (Morikawa et al. 2020). Specifically, under current fishing pressure and stock-recruitment relationship of this stock, the average value of M for the previous 3 years must be 0.432 or less. In this report, the average value of M for the previous 3 years (2018 to 2020 average) was estimated to be 0.677, so we continued to be unable to consider a reference point plan or a Harvest Control Rule draft for this stock.

The catch strategy for this stock is to "avoid operations which deliberately catch this stock," which includes maximum avoidance of incidental catch even by operations targeting other fish species, avoidance of operations in sites where small crabs can be caught in nets, and releasing as many mature individuals as possible. It is essential to preserve the SSB as much as possible.

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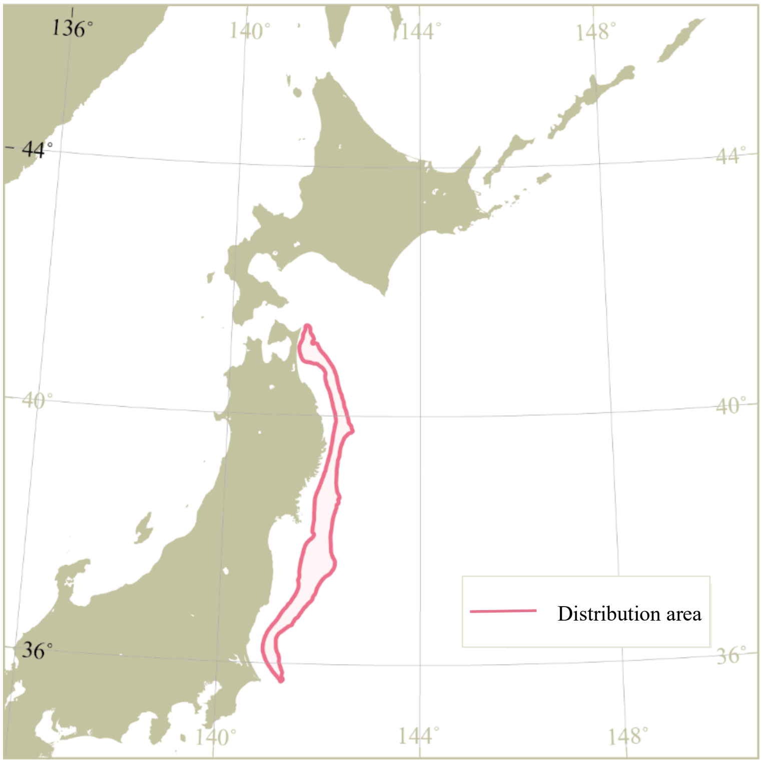


Fig. 2-1. Distribution of snow crabs in the North Pacific (excluding Hokkaido)

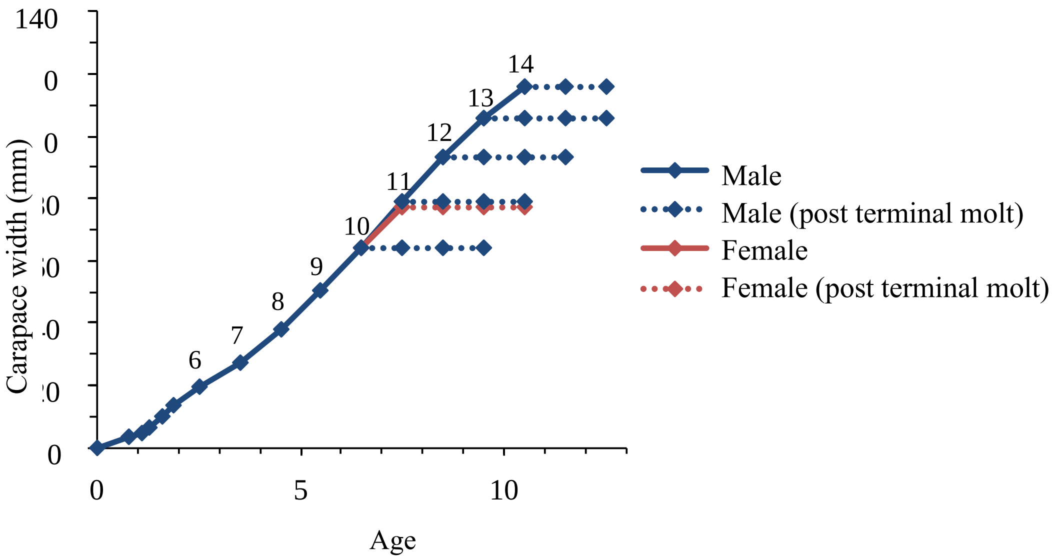


Fig. 2-2. Relationship between age, molt-age, and carapace width of snow crabs in the North Pacific off Honshu Island, Japan

Numbers indicate molt-age. Assuming that individuals molt once per year after the 6th instar, recruitment age in our stock calculations was the 8th instar (age 5 years old). Growth was assumed to be the same in both sexes up to the 9th instar.

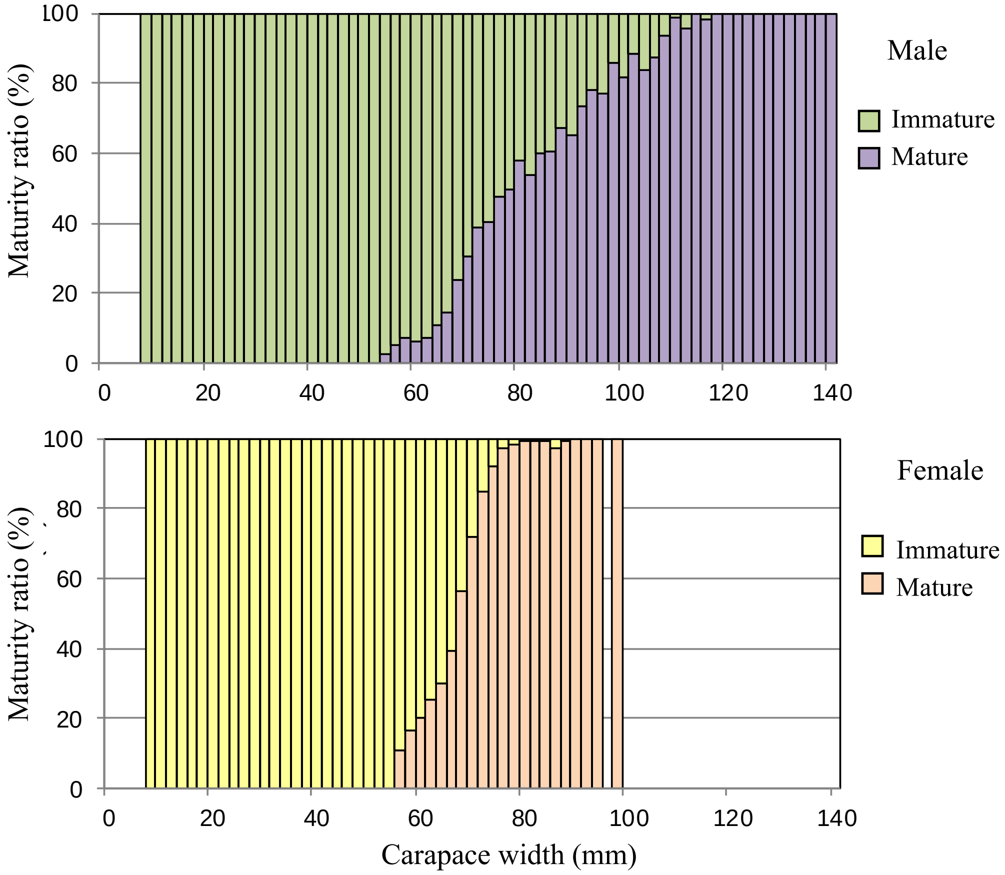


Fig. 2-3. Maturity ratio of snow crabs by carapace width (1997 to 2020 fishing seasons)

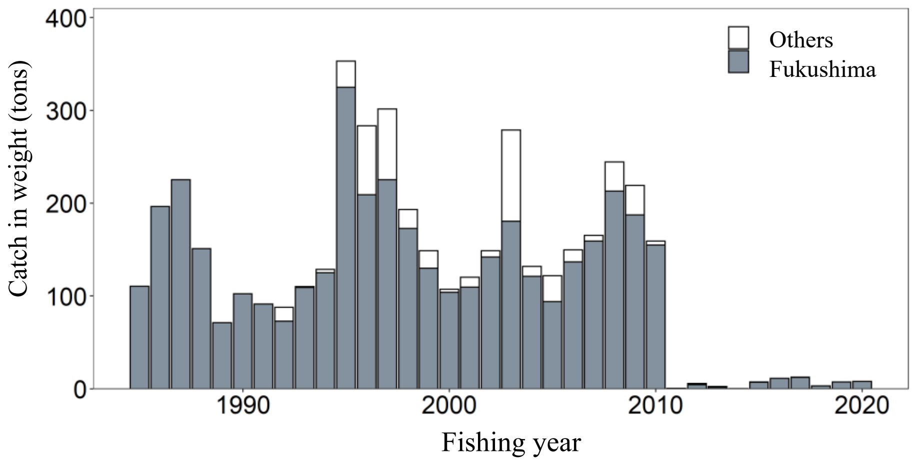


Fig. 3-1. Trends in catch in weight of snow crabs

Catch in weight for Fukushima in the 1985 to 1991 fishing seasons are for Soma Port only.

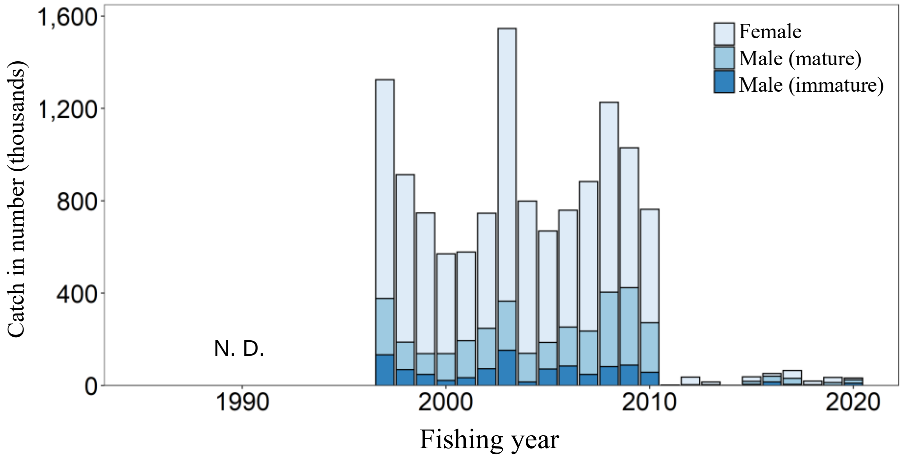


Fig. 3-2. Catch in number by instar

For more information about catch in number by instar for males, see Appendix 5.

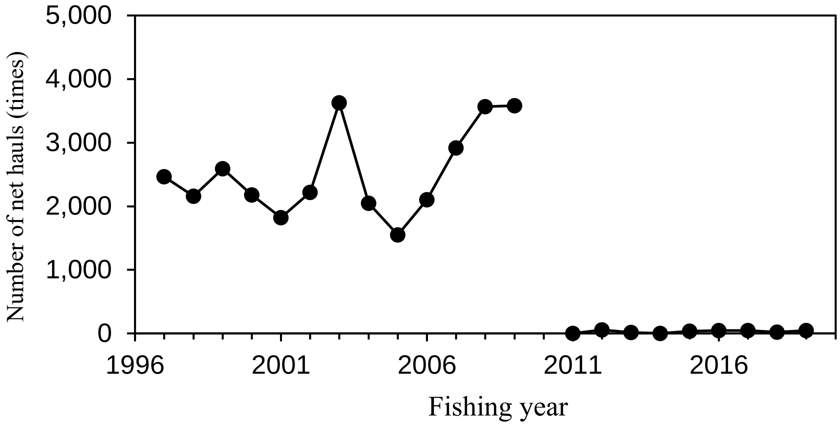


Fig. 3-3. Trends in fishing effort (number of towing with non-zero catches) (offshore trawl in Fukushima)

Effort levels in the 2010 fishing season were not available because the data of Offshore Trawl Report was lost due to the Earthquake.

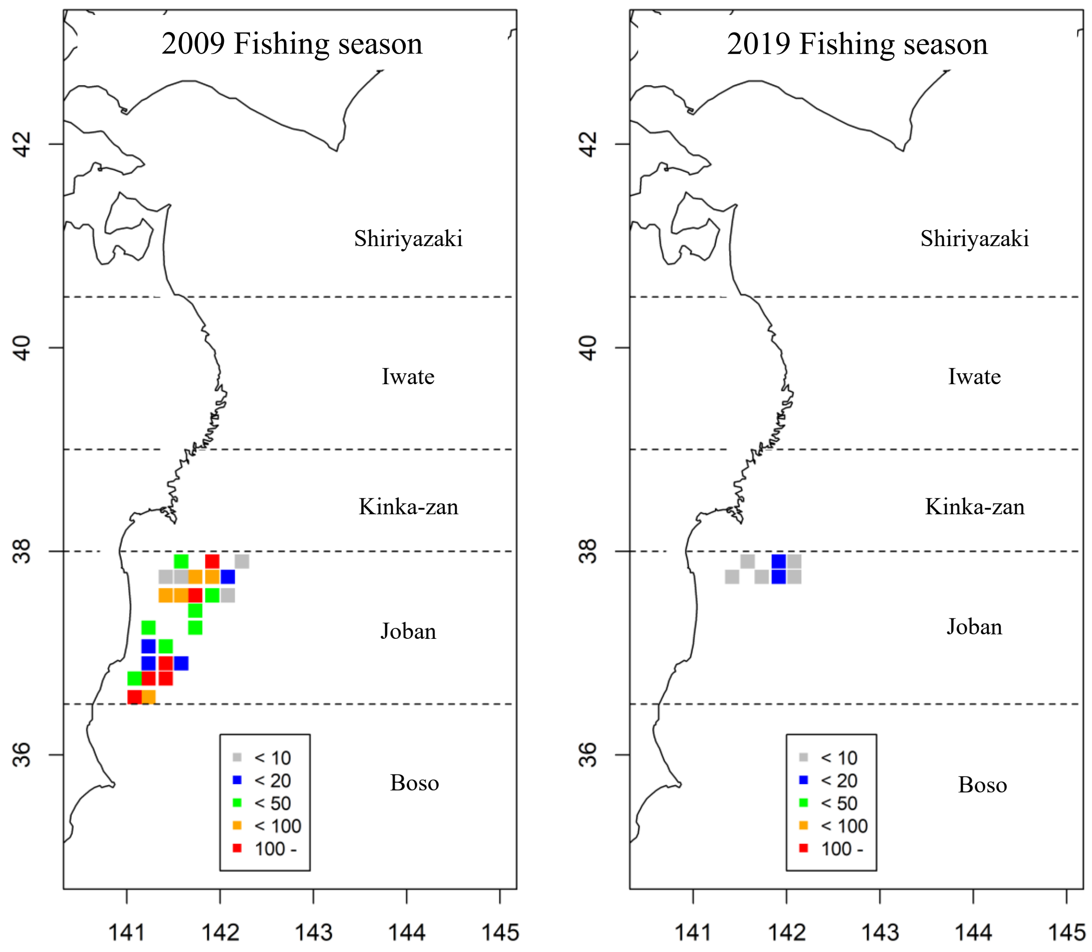


Fig. 3-4. Comparison of fishing effort (number of towing with non-zero catches) in the pre-Earthquake period (2009 fishing season) and the 2019 fishing season

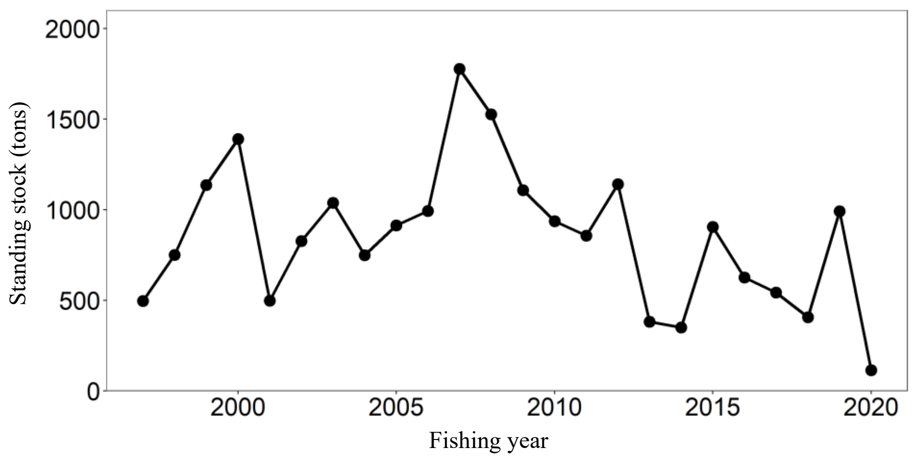


Fig. 4-1. Trends in standing stock based on bottom-trawl surveys

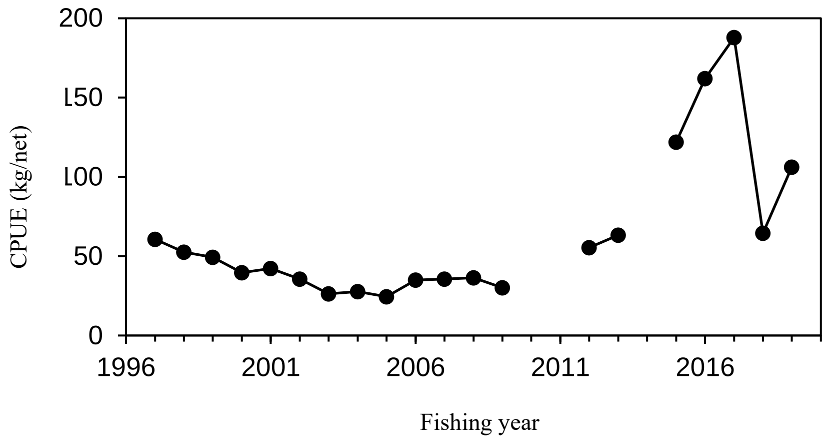


Fig. 4-2. CPUE for snow crabs in Fukushima offshore trawling

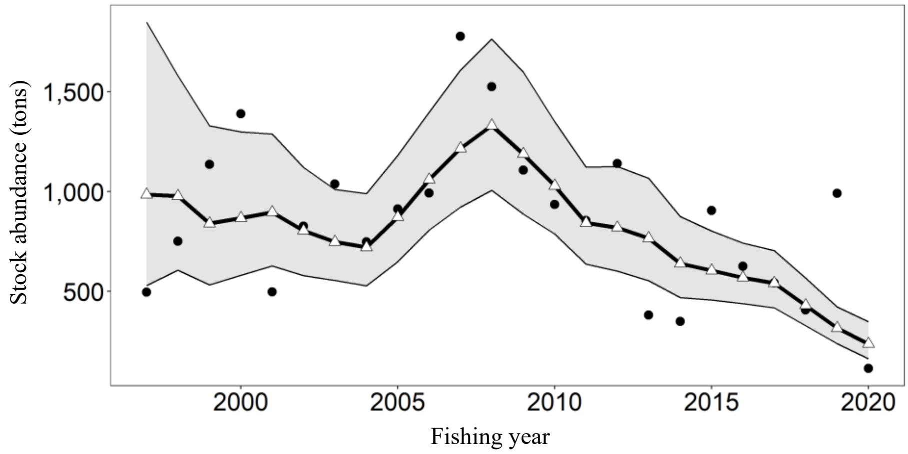


Fig. 4-3. Trends in fishable stock (triangles) and standing stock based on bottom-trawl surveys (black dots)

The shaded area indicates the 95% confidence interval for estimated values.

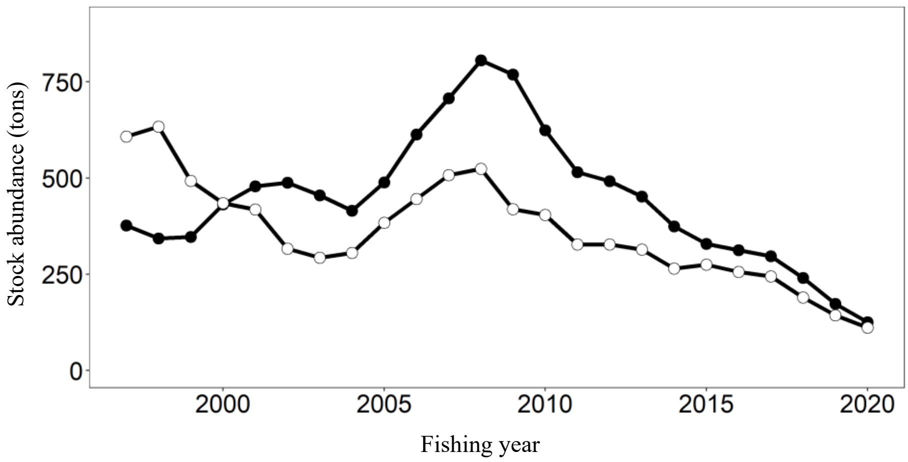


Fig. 4-4. Trends in fishable stock by sex (males: black dots, females: white dots)

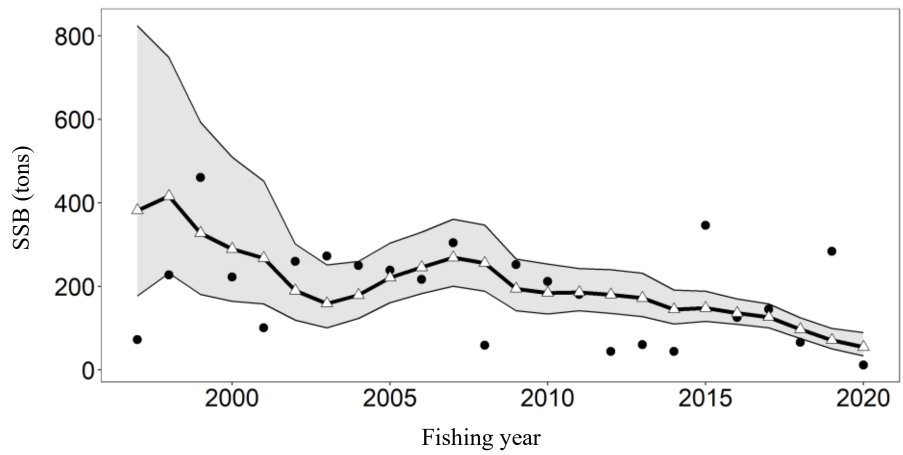


Fig. 4-5. Trends in SSB

Triangles indicate JASAM estimates, and the shaded area indicates the 95% confidence interval for estimated values.

Black dots indicate current SSB based on standing stock in bottom-trawl surveys.

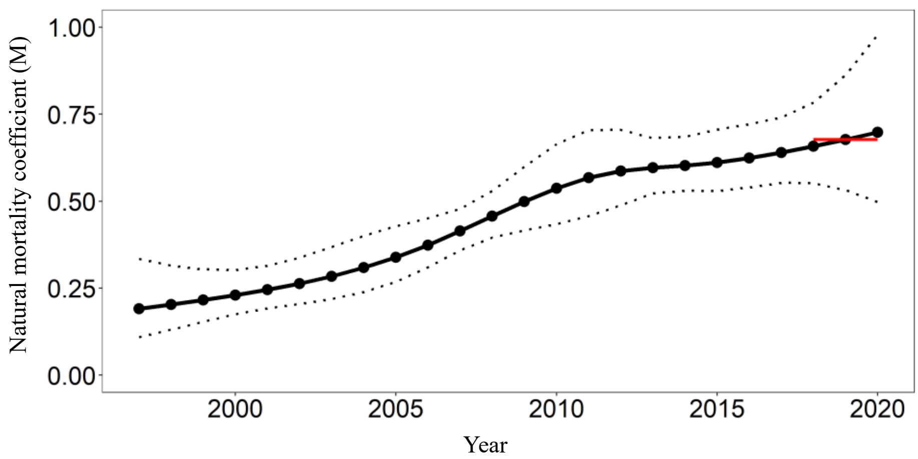


Fig. 4-6. Trends in natural mortality coefficient (M)

The dotted line indicates the 95% confidence interval, and the red line indicates current M (average value in 2018 to 2020).

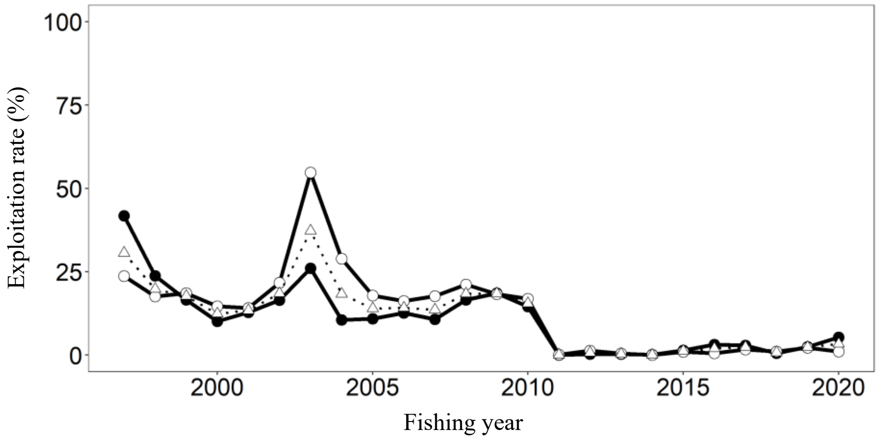


Fig. 4-7. Trends in exploitation rate (males: black dots, females: white dots, total males and females: triangles)

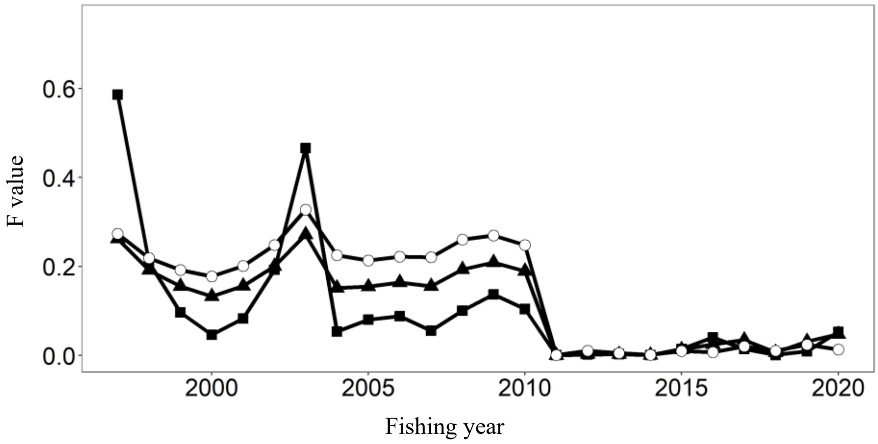


Fig. 4-8. Trends in F value (males (immature): black squares, males (mature): black triangles, females: white dots)

Mature and immature are defined based on completion of the terminal molt.

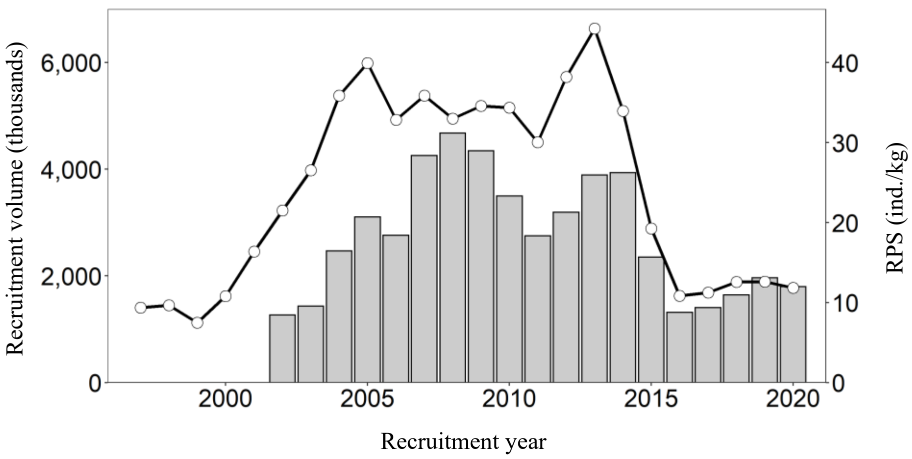


Fig. 4-9. Trends in recruitment (line graph) and recruitment per spawning (bar graph)

Recruitment per spawning values correspond to recruitment year. In this stock, the period until recruitment is assumed to be 5 years, so SSB in the 1997 fishing season corresponds to the value for recruitment in the 2002 fishing season.

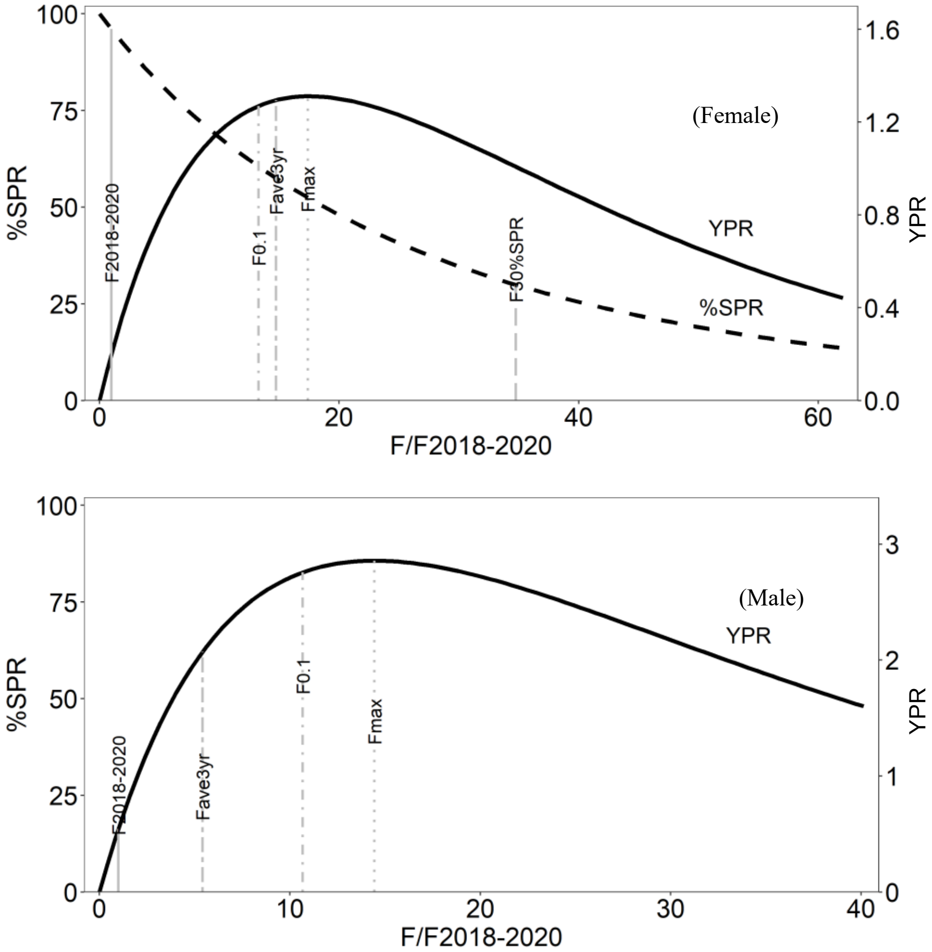


Fig. 4-10. Relationship between F value by sex and YPR and %SPR

The horizontal axis indicates the ratio to current fishing pressure (F2018-2020). Assuming current M (average value in 2018 to 2020), calculations were performed using a 50% survival rate for non-fishable small individuals that were released after incidental catch.

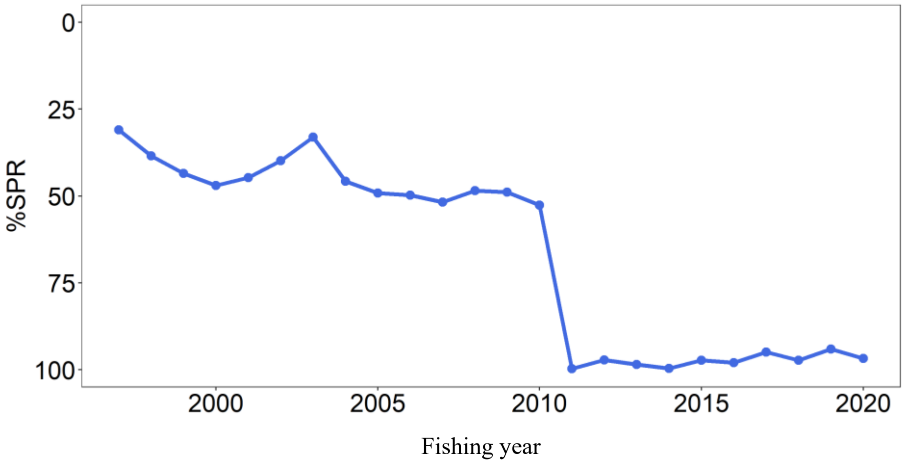


Fig. 4-11. Trends in %SPR value by each fishing year

The %SPR indicates the ratio of SSB with fishing to SSB without fishing. When F is high (low), then %SPR is smaller (larger). Because M changes annually in this stock, the %SPR value corresponds to M in each year. When M is high, then %SPR is larger even with an unchanged F value, and when M is low, then it is smaller.

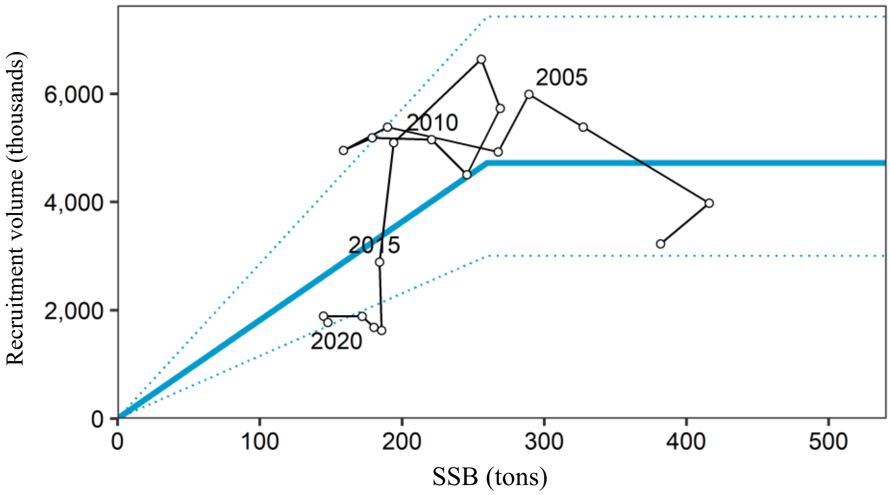


Fig. 4-12. Relationship between SSB and recruitment (stock-recruitment relationship)

The solid blue line in the figure indicates the stock-recruitment relationship model based on SSB in 1997 to 2013 and recruitment in 2002 to 2018, as calculated in the 2019 stock assessment. The white dots in the figure indicate the SSB and recruitment for each year, as calculated in the 2021 stock assessment. The numbers in the figure indicate the year class (recruitment year) of recruited stock. Stock-recruitment relationship was represented using a hockey-stick model (HS) for stock-recruitment relationship with autocorrelation, and parameters were estimated using the least squares method. The dotted lines above and below the stock-recruitment relationship (solid blue line) in the figure represent the interval estimated to contain 90% of observed data in the assumed stock-recruitment relationship.

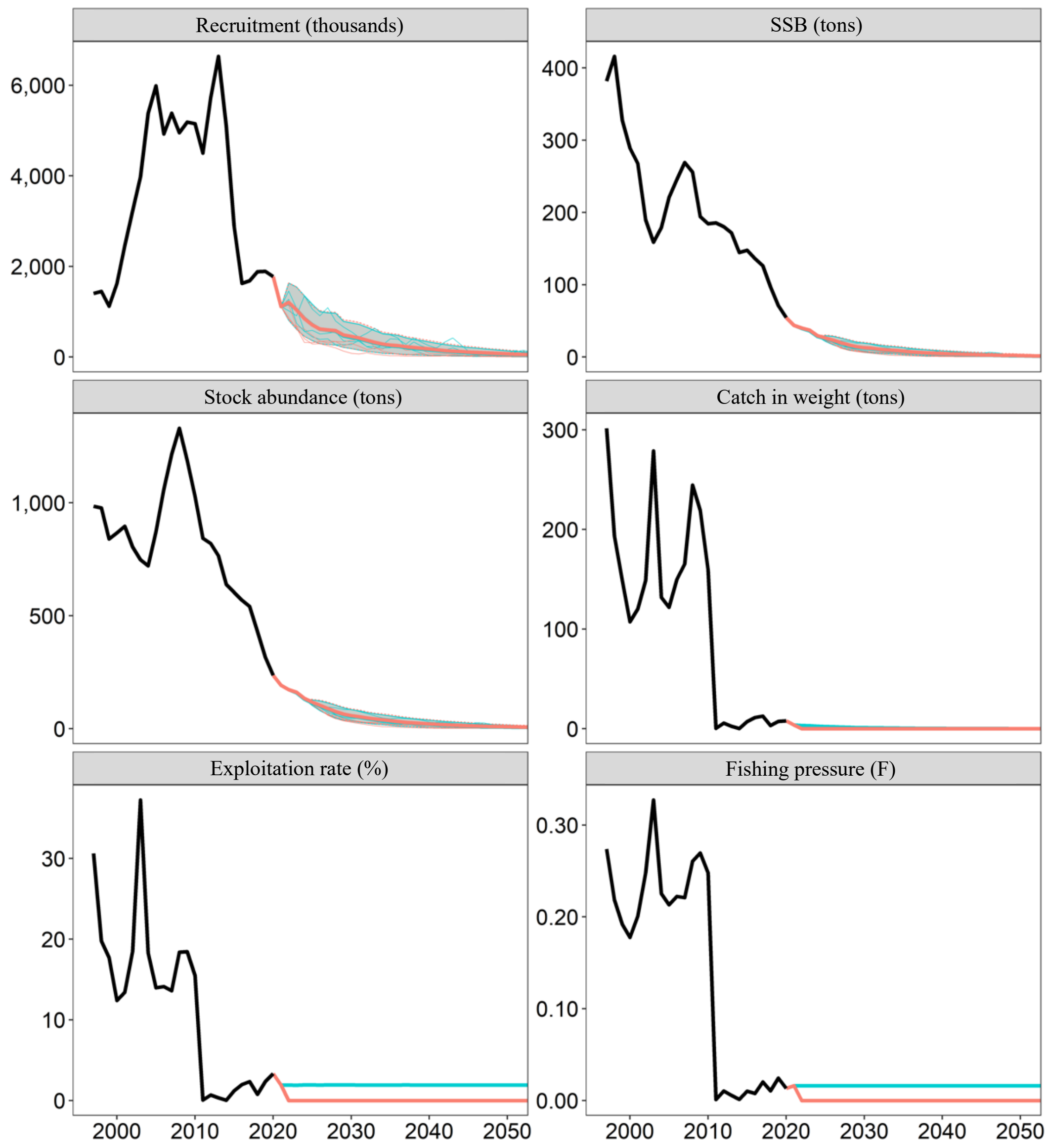


Fig. 5-1. Future forecasts if current fishing pressure (F2018-2020) is continued (green), and if catch is set to zero (red)

The horizontal axis indicates the fishing year, the bold line indicates average values, the shaded area indicates the prediction interval which contains 80% of simulation results, and the thin lines indicate 3 future forecasts.

Table 2-1. Carapace width (mm) used for molt-age analysis by cohort slicing method

Molt-age	Male		Molt-age	Female	
	More than	Less than		More than	Less than
8th instar	28	42	8th instar	28	42
9th instar	42	56	9th instar	42	56
10th instar	56	74	10th instar, pre terminal molt (immature)	56 or more	
11th instar	74	86	11th instar, post terminal molt (mature)	—	
12th instar	86	98			
13th instar, pre terminal molt	98 or more				
13th instar, post terminal molt	98	110			
14th instar, post terminal molt	110 or more				

Table 3-1. Catch in weight of snow crabs by prefecture (tons)

Fishing year	Aomori	Iwate	Miyagi	Fukushima	Ibaraki	Total	Fukushima share (%)
1985	—	—	—	110.5	—	110.5	—
1986	—	—	—	196.3	—	196.3	—
1987	—	—	—	225.1	—	225.1	—
1988	—	—	—	151.1	—	151.1	—
1989	—	—	—	71.3	—	71.3	—
1990	—	—	—	102.3	—	102.3	—
1991	—	—	—	91.3	—	91.3	—
1992	—	—	—	72.8	15.1	87.9	—
1993	—	—	—	109.3	0.8	110.1	—
1994	—	—	2.0	125.2	1.6	128.8	—
1995	19.6	—	3.7	324.7	5.1	353.1	—
1996	31.0	0	43.0	209.1	0.1	283.2	73.8
1997	3.8	0.2	72.3	225.2	0.1	301.6	74.7
1998	1.1	0	19.4	172.7	0	193.2	89.4
1999	8.8	0	9.9	130.0	0	148.7	87.4
2000	1.0	0.3	2.1	104.0	0	107.4	96.8
2001	0.1	0.2	4.0	109.4	6.6	120.3	90.9
2002	0	1.3	5.5	141.9	0	148.7	95.4
2003	0.3	0.1	7.5	180.6	90.2	278.7	64.8
2004	0.4	0	4.0	121.1	6.4	131.9	91.8
2005	0.3	0.1	4.0	94.0	23.5	121.8	77.2
2006	0	0	3.8	136.8	9.1	149.8	91.4
2007	0	0.2	2.9	159.1	3.2	165.4	96.2
2008	0	0.3	15.7	212.9	15.7	244.5	87.1
2009	0	0.1	5.5	187.3	26.2	219.1	85.5
2010	0	0	1.1	154.9	3.2	159.3	97.3
2011	0.3	0	0.2	0	0	0.5	0
2012	0.4	0.3	0.3	4.6	0	5.6	82.0
2013	0.7	0	0.4	1.5	0	2.6	57.0
2014	0	0	0.3	0	0	0.3	3.6
2015	0	0	0	7.2	0	7.2	99.4
2016	0.1	0	0	11.1	0	11.2	99.1
2017	0	0.5	0.1	12.1	0	12.7	95.5
2018	0	0	0.1	3.2	0	3.3	97.9
2019	0	0	0	7.4	0	7.4	100.0
2020	0	0	0	7.9	0	7.9	100.0

Values prior to the 1995 fishing season (excluding Fukushima) include other species of crabs.
Fukushima vessels were forced to suspend operations in the 2011 fishing season, and only experimental operations have been conducted since the 2012 fishing season.
Catch in weight values for Fukushima in the 1985 to 1991 fishing seasons are for Soma Port only.
Catch in weight is calculated by fishing year (from July to June of the following year). Fishing season is from December to March of the following year.

Table 4-1. Trends in stock abundance, SSB after the fishing season ends, catch in weight, F value, and exploitation rate of snow crab fishable stock (males with carapace width of 80 mm or more and mature females) estimated using swept-area method (Trawl) and JASAM

			1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Population Size (thousands)	Male	Trawl	816	1,025	1,653	2,959	1,007	1,291	1,571	1,117	1,898	1,936	4,721	4,538
		JASAM	1,130	1,021	1,146	1,381	1,532	1,482	1,406	1,427	1,764	2,159	2,528	2,788
	Female	Trawl	1,556	2,559	4,457	2,350	1,239	2,979	3,908	3,239	2,876	2,749	4,017	1,574
		JASAM	3,999	4,122	3,291	2,951	2,720	2,302	2,155	2,282	2,708	3,127	3,661	3,881
	Trawl total		2,371	3,584	6,110	5,309	2,247	4,270	5,479	4,357	4,774	4,684	8,738	6,111
	JASAM total		5,129	5,143	4,437	4,332	4,252	3,784	3,561	3,709	4,472	5,286	6,189	6,669
Stock abundance (tons)	Male	Trawl	260	357	469	1043	307	417	507	315	506	600	1,220	1,313
		JASAM	377	343	347	432	478	488	455	415	489	614	708	806
	Female	Trawl	236	394	667	346	191	410	531	434	407	392	557	213
		JASAM	608	634	492	435	418	316	293	305	383	446	508	524
	Trawl total		496	751	1,135	1,389	497	826	1,038	749	913	992	1,777	1,525
	JASAM total		985	977	840	867	896	804	748	721	872	1,060	1,215	1,330
SSB (tons)	Trawl		63	206	430	210	97	252	268	256	252	236	347	72
	JASAM		382	416	327	289	268	190	159	179	221	246	269	256
Catch in weight (tons)	Male		157.6	81.5	57.6	43.7	61.4	80.2	118.4	43.7	53.4	77.6	75.6	133.5
	Female		144	111.7	91.1	63.7	58.9	68.6	160.4	88.2	68.4	72.1	89.8	111
	Total		301.6	193.2	148.7	107.4	120.3	148.7	278.7	131.9	121.8	149.8	165.4	244.5
F value	Male (immature)		0.586	0.209	0.097	0.046	0.083	0.193	0.466	0.054	0.080	0.088	0.056	0.100
	Male (mature)		0.263	0.192	0.155	0.132	0.156	0.201	0.271	0.152	0.155	0.164	0.155	0.193
	Female		0.274	0.219	0.192	0.178	0.201	0.248	0.327	0.225	0.213	0.222	0.221	0.261
	Total		0.366	0.220	0.195	0.132	0.144	0.205	0.466	0.202	0.150	0.152	0.146	0.203
Exploitation rate (%)	Male		41.8	23.8	16.6	10.1	12.8	16.4	26.0	10.5	10.9	12.7	10.7	16.6
	Female		23.7	17.6	18.5	14.6	14.1	21.7	54.8	28.9	17.8	16.2	17.7	21.2
	Total		30.6	19.8	17.7	12.4	13.4	18.5	37.3	18.3	14.0	14.1	13.6	18.4

			2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Population Size (thousands)	Male	Trawl	1,825	1,780	1,894	3,101	953	937	1,010	1,585	959	898	1,312	336
		JASAM	2,528	2,089	1,762	1,667	1,534	1,268	1,165	1,179	1,093	845	593	432
	Female	Trawl	3,940	3,143	2,375	624	811	624	4,825	2,031	2,270	1,001	3,883	159
		JASAM	3,312	2,903	2,437	2,425	2,284	2,033	2,072	2,200	1,981	1,467	990	725
	Trawl total		5,766	4,923	4,269	3,725	1,764	1,561	5,835	3,617	3,229	1,899	5,195	495
	JASAM total		5,840	4,992	4,199	4,092	3,818	3,302	3,237	3,379	3,073	2,311	1,583	1,157
Stock abundance (tons)	Male	Trawl	608	498	537	1,056	269	269	264	389	263	278	429	89
		JASAM	769	624	515	492	452	375	329	313	297	241	173	125
	Female	Trawl	498	437	319	84	111	81	641	236	280	129	562	24
		JASAM	419	404	328	328	314	265	275	256	244	189	143	111
	Trawl total		1,107	935	856	1,141	381	350	905	626	543	407	992	114
	JASAM total		1,188	1,028	843	820	766	639	604	569	541	430	316	237
SSB (tons)	Trawl		313	276	240	60	83	62	493	180	213	98	433	18
	JASAM		194	184	186	180	172	145	148	136	126	97	71	55
Catch in weight (tons)	Male		142.5	91	0.3	1.3	1.1	0.3	4.5	9.7	8.6	1.3	4.2	6.7
	Female		76.6	68.2	0.3	4.3	1.5	0	2.7	1.5	4.1	2	3.2	1.2
	Total		219.1	159.3	0.5	5.6	2.6	0.3	7.2	11.2	12.7	3.3	7.4	7.9
F value	Male (immature)		0.137	0.104	0.001	0.002	0.003	0.001	0.015	0.041	0.015	0.001	0.009	0.053
	Male (mature)		0.209	0.190	0.000	0.002	0.003	0.001	0.013	0.025	0.035	0.007	0.032	0.048
	Female		0.270	0.248	0.001	0.010	0.006	0.001	0.010	0.008	0.020	0.011	0.025	0.013
	Total		0.204	0.168	0.001	0.007	0.003	0.000	0.012	0.020	0.024	0.008	0.024	0.034
Exploitation rate (%)	Male		18.5	14.6	0.1	0.3	0.2	0.1	1.4	3.1	2.9	0.6	2.4	5.3
	Female		18.3	16.9	0.1	1.3	0.5	0.0	1.0	0.6	1.7	1.0	2.2	1.1
	Total		18.5	15.5	0.1	0.7	0.3	0.0	1.2	2.0	2.3	0.8	2.3	3.3

Table 4-2. Natural mortality coefficient estimated by JASAM (including all instars, both sexes, and all maturity)

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
M	0.191	0.203	0.216	0.230	0.245	0.263	0.284	0.309	0.339	0.374	0.414	0.457	0.499

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Current M
M	0.537	0.567	0.587	0.596	0.602	0.611	0.624	0.640	0.658	0.677	0.698	0.677

Current M is the average of the previous 3 years (2018 to 2020).

Table 5-1. Trends in average future SSB and catch in weight

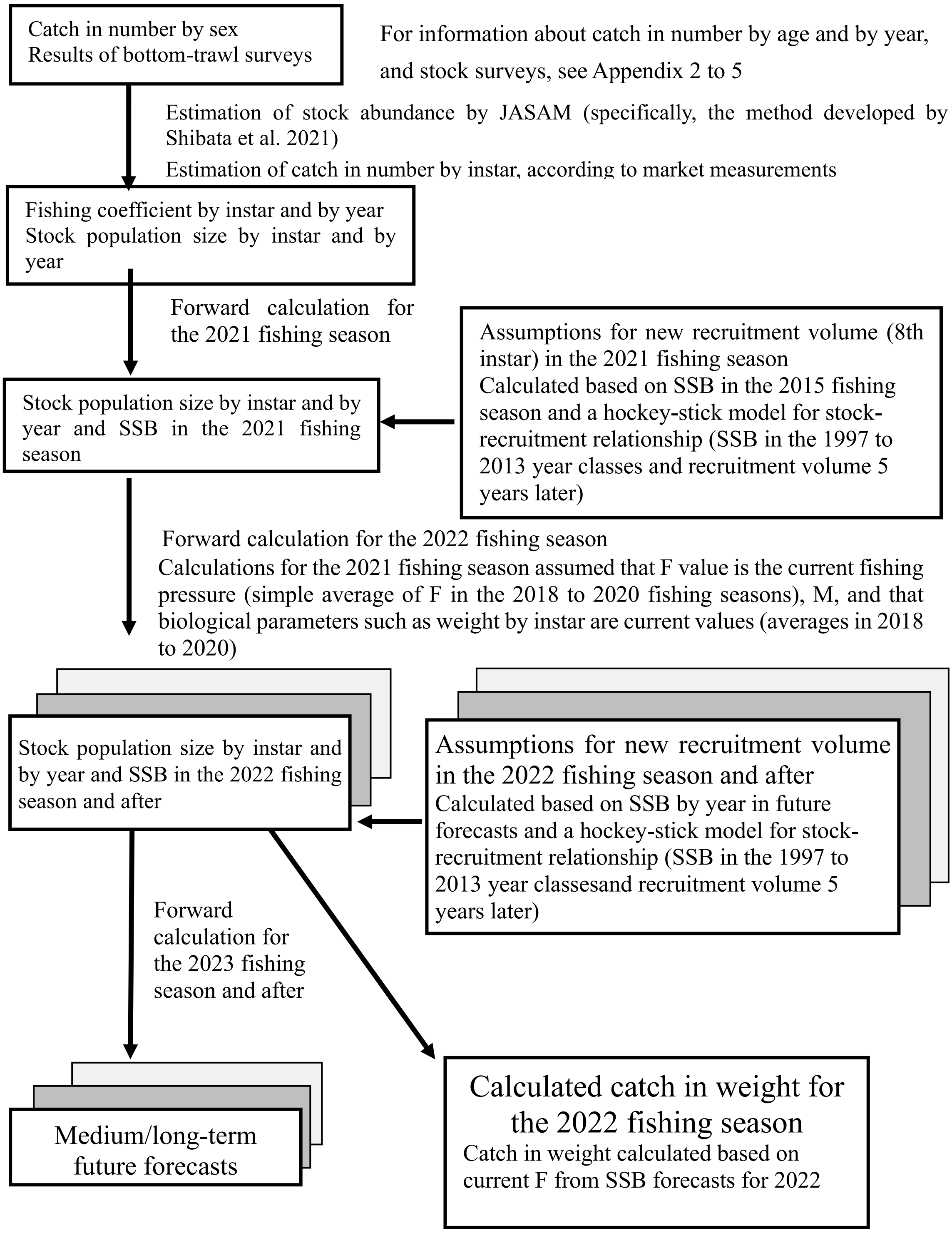
a) Trends in average SSB

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2042	2052
F2018-2020	44	40	36	29	25	22	19	16	14	12	12	10	4	1
[Reference] F = 0	44	40	37	29	26	23	20	17	14	13	12	11	4	2

b) Trends in average catch in weight

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2042	2052
F2018-2020	3.7	3.3	3.0	2.5	2.2	1.9	1.7	1.4	1.2	1.1	1.0	0.9	0.3	0.1
[Reference] F = 0	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Appendix 1 Flow of Stock Assessment



Appendix 2 Calculation Methods

(1) Stock Calculation Methods

Standing stock (in number and weight) of the North Pacific stock off Honshu Islands, Japan of snow crabs was estimated by an swept-area method using the number of individuals and carapace width composition of snow crabs collected in bottom-trawl surveys (Appendix 3). Using this standing stock data as an abundance index (observed value), we applied JASAM (just another state-space stock assessment model, Shibata et al. 2021) which was developed based on SAM (state-space stock assessment model, Nielsen and Berg 2014) and estimated parameters for stock abundance and stock dynamics. See Shibata et al. (2021) for details of the model.

1. Fishing mortality coefficient F

Catch targets in this stock are defined as males with a carapace width of 80 mm or more (immature/mature) and mature females. In addition, according to Kitagawa (2000), the larger individuals of this stock are found at greater depths. Therefore, the spatial distribution was expected to be divided between immature and mature individuals, and *F* was estimated in 3 groups: immature males, mature males, and mature females. Furthermore, due to the effects of the Great East Japan Earthquake in 2011 (hereinafter referred to as "the Earthquake"), *t* represents the year (*t* = 1997, ..., 2020), and *t* was assumed to fluctuate in a random walk (RW) pattern across all categories, except in 2010:

$$\ln\left(F_{k,t+1}\right) = \ln\left(F_{k,t}\right) + \varepsilon_{k,t}, \tag{1}$$
$$\varepsilon_{k,t} \sim \mathrm{MVN}(0, \textstyle\sum_F), \tag{2}$$

The subscript letter *k* indicates groups, specifically *k* = 1 (immature males), *k* = 2 (mature males), and *k* = 3 (mature females). When *t* is 2010, there was a sudden decrease in fishing pressure after the Earthquake. Therefore, the following fixed result *EQ* was used because RW was not appropriate:

$$\ln\left(F_{k,t+1}\right) = \ln\left(F_{k,t}\right) + EQ_k + \varepsilon_{k,t}, \tag{3}$$

However, $\varepsilon = (\varepsilon_{k,1997,\ldots,}\varepsilon_{k,2017})$ is a process error vector following multivariate normal distribution (MVN) which is defined by the variance-covariance matrix Σ (the upper triangular area is omitted):

$$\textstyle\sum_F = \rho_k \sigma_{F,k} \sigma_{F,\tilde{k}} = \begin{pmatrix} \sigma_{F,k=1}^2 & & \\ \rho_{k=1}\sigma_{F,k=1}\sigma_{F,k=2} & \sigma_{F,k=2}^2 & \\ \rho_{k=3}\sigma_{F,k=3}\sigma_{F,k=1} & \rho_{k=2}\sigma_{F,k=2}\sigma_{F,k=3} & \sigma_{F,k=3}^2 \end{pmatrix}$$

In addition, we also considered models like the following where *ρ* and *σ* switch after the Earthquake:

$$\rho_k = \begin{cases} \frac{1}{1+\exp\left(-T_{\rho_k}\right)} & \text{If } t < 2011 \\ \frac{1}{1+\exp\left(-\left(T_{\rho_k}+T_{\rho}\right)\right)} & \text{otherwise} \end{cases} \tag{4}$$

$$\ln(\sigma_{F,k}) = \begin{cases} \ln(\sigma_{F,k}) & \text{If } t < 2011 \\ \ln(\sigma_{F,k}) + T_{\sigma_{F,k}} & \text{otherwise} \end{cases} \tag{5}$$

2. Natural mortality coefficient M

Changes by year in the natural mortality coefficient M were assumed to follow a second-order difference RW according to the selection results of the model proposed by Shibata et al. (2021). σ_M indicates standard deviation of RW:

$$\ln\left(M_{t+1}\right) \sim \text{Normal}(2\ln\left(M_t\right) - \ln\left(M_{t-1}\right), \sigma_M^2) \tag{6}$$

3. Population dynamics model

Stock population size is N, age (instar) is a (a = 8, 9, ... , 14), and the number of years after terminal molt was completed is j (j = 0, 1, 2). In these equations, j = 0 indicates an immature individual that has not completed their terminal molt, and j = 1 indicates that terminal molt was completed (within the previous year) and j = 2 indicates the 2nd year or longer after terminal molt was completed.

a) Method for estimating stock population size in the 8th instar

In this stock, the timing of recruitment is assumed to be in the 8th instar. The recruitment population of males and females is assumed to be equal, and the stock population size of individuals in the 8th instar was calculated using a first-order difference RW:

$$\ln\left(N_{a=8,j=0,t+1}\right) \sim \text{Normal}(\ln\left(N_{a=8,j=0,t}\right), \sigma_{rec}^2)) \tag{7}$$

b) State model for male individual count

The molt between the 8th instar and the 9th instar is not considered to be the terminal molt. In subsequent molts, except the 14th instar when all individuals complete their terminal molt, there are both immature individuals which continue to advance in instar every year without completing their terminal molt, and individuals which complete their terminal molt and reach maturity. For this reason, we considered completion and incompletion of terminal molt for each instar. In addition, because the catch targets of this stock have a carapace width of 80 mm or more, we considered fishing mortality for individuals in the 11th instar with a carapace width of 80 mm or more, and all individuals in the 12th instar or older. It was assumed that the number of individuals in the 10th to 11th instar multiplied by r is the number of catch targets. Individuals that completed their terminal molt in the 10th and 11th instar with a carapace width less than 80 mm are not considered to be catch targets for their entire lifetime. Individuals that completed their terminal molt remain in the same instar also in the following year, so individuals in the 2nd year or longer after terminal molt was completed are mixed in with the previous year’s 2nd year individuals, making this a plus group. The state model for each instar group is shown in equations (8) to (20) (Supplementary Figure 2-1).

・8th instar to 9th instar (a = 8)

$$\ln\left(N_{a+1,j=0,t+1}\right) = \ln\left(N_{a,j=0,t}\right) - M_t \tag{8}$$

・9th instar to 10th instar (a = 9)

$$\ln\left(N_{a+1,j=0,t+1}\right) = \ln\left(N_{a,j=0,t}\right) - M_t + \ln\left(1 - p_{a,t}\right) \tag{9}$$

$$\ln\left(N_{a+1,j=1,t+1}\right) = \ln\left(N_{a,j=0,t}\right) - M_t + \ln\left(p_{a,t}\right) \tag{10}$$

$$\ln\left(N_{a+1,j=2,t+1}\right) = \ln\left(\textstyle\sum_{j=1}^{2} N_{a+1,j,t} \exp(M_t)\right) \tag{11}$$

・10th instar to 11th instar (a = 10)

$$\ln\left(N_{a+1,j=0,t+1,74-80}\right) = \ln\left(N_{a,j=0,t}\right) - M_t + \ln\left(1 - p_{a,t}\right) + \ln(1 - r) \tag{12)*}$$

$$\ln\left(N_{a+1,j=0,t+1,80-86}\right) = \ln\left(N_{a,j=0,t}\right) - M_t + \ln\left(1 - p_{a,t}\right) + \ln(r) \tag{13)*}$$

$$\ln\left(N_{a+1,t+1,74-80}\right) = \ln\left(N_{a,j=0,t} \exp\left(-M_t\right) p_{a,t} (1 - r) + \textstyle\sum_{j=1}^{2} N_{a+1,j,t,74-80} \exp(-M_t)\right) \tag{14)*}$$

$$\ln\left(N_{a+1,t+1,80-86}\right) = \ln\left(N_{a,j=0,t} \exp\left(-M_t\right) p_{a,t} r + \textstyle\sum_{j=1}^{2} N_{a+1,j,t,80-86} \exp(-M_t - F_{k=2,t})\right) \tag{15)*}$$

・11th instar to 12th instar (a = 11)

$$\ln\left(N_{a+1,j=0,t+1}\right) = \ln\left(\left(N_{a,j=0,t,74-80} \exp\left(-M_t\right) + N_{a,j=0,t,80-86} \exp\left(-M_t - F_{k=1,t}\right)\right)\left(1 - p_{a,t}\right)\right) \tag{16}$$

$$\ln\left(N_{a+1,t+1}\right) = \ln\left(\left(N_{a,j=0,t,74-80} \exp\left(-M_t\right) + N_{a,j=0,t,80-86} \exp\left(-M_t - F_{k=1,t}\right)\right) p_{a,t} + \textstyle\sum_{j=1}^{2} N_{a+1,j,t} \exp(-M_t - F_{k=2,t})\right) \tag{17}$$

・12th instar to 13th instar (a = 12)

$$\ln\left(N_{a+1,j=0,t+1}\right) = \ln\left(N_{a,j=0,t}\right) - M_t - F_{k=1,t} + \ln\left(1 - p_{a,t}\right) \tag{18}$$

$$\ln\left(N_{a+1,t+1}\right) = \ln\left(N_{a,j=0,t} \exp\left(-M_t - F_{k=1,t}\right) p_{a,t} + \textstyle\sum_{j=1}^{2} N_{a+1,j,t} \exp(-M_t - F_{k=2,t})\right) \tag{19}$$

・13th instar to 14th instar (a = 13)

$$\ln\left(N_{a+1,t+1}\right) = \ln\left(N_{a,j=0,t} \exp\left(-M_t - F_{k=1,t}\right) + \textstyle\sum_{j=1}^{2} N_{a+1,j,t} \exp(-M_t - F_{k=2,t})\right) \tag{20}$$

*However, $r = 1/(1 + \exp(-T_r))$

c) State model for females

There are no individual females that reach maturity between the 8th and 10th instars, and all individuals that molt and enter the 11th instar complete their terminal molt and reach maturity. In addition, only mature female individuals are catch targets.

・8th instar to 9th instar, 9th instar to 10th instar (a = 8, 9)

$$\ln\left(N_{a+1,j=0,t+1}\right)=\ln\left(N_{a,j,t}\right)-M_t \quad (21)$$

・10th instar to 11th instar (a = 10)

$$\ln\left(N_{a+1,t+1}\right)=\ln\left(N_{a,j=0,t}\exp(-M_t)+\sum_{j=1}^{2}N_{a+1,j,t}\exp(-M_t-F_{k=2,t})\right) \quad (22)$$

d) Estimation of terminal molt rate

Terminal molt rate was modeled by a function of age (instar). Considering the possibility that one reason for the recent decline in stock abundance is an annual change in the terminal molt rate, we assumed that terminal molt rate parameters change in a RW pattern.

$$p_{a,t}=1/(1+\exp(-(\beta_{0,t}+\beta_1\times a))) \quad (23)$$

$$\beta_{0,t+1}\sim\mathrm{Normal}(\beta_{0,t},\sigma_{\beta_0}) \quad (24)$$

4. Standing stock based on bottom-trawl surveys

Standing stock population size estimated using a swept-area method (no consideration of catch efficiency) is n, and n is based on catch efficiency q from the true stock population size N (Supplementary Table 2-1). The number of years after terminal molt was completed is unknown in bottom-trawl surveys, so only the completion or incompletion of terminal molt can be determined (u = 0, 1). The likelihood functions for stock population size are described in equations (25) and (26). Likewise, males in the 11th instar (carapace width of 74 to 86 mm) are divided as to whether they are fishable based on the 80 mm carapace width minimum, so this instar class was sorted into carapace width of 74 mm to 80 mm and 80 mm to 86 mm, and likelihood was calculated for both groups. The coefficient of variation (CV) is the known CV obtained from bottom-trawl surveys. In addition, survey errors were considered in order to avoid underestimating the uncertainty of stock population size estimates (Kitakado and Okamura 2009). The section where CV = 1 was complemented according to Taylor's power law.

Catch efficiency q of nets used for bottom-trawl surveys, sorted by carapace width, is expressed by equation (27) (Supplementary Figure 2-2). Average carapace widths for each instar based on annual trawl surveys is used in $cw_{a,t}$. The factor $q_{a,t}$ was treated as a random effect in consideration of estimation errors in catch efficiency. The average values of γ_1 to γ_3 and the variance-covariance matrix are based on the models of Hattori et al. (2014).

・Likelihood function for stock population size

$$\ln\left(n_{a,u,t}\right)\sim\mathrm{Normal}(\ln\left(q_{a,t}N_{a,u,t}\right),\log\left(1+\omega_{a,u,t}^2\right)+\log\left(1+CV_{a,u,t}^2\right)), \quad (25)$$

$$\ln\left(\omega_{a,u,t}\right)\sim\mathrm{Normal}(\mu_\omega,\sigma_\omega^2), \quad (26)$$

・Catch efficiency by carapace width size

$$q_{a,t}=\gamma_0/(1+\exp\left(-(\gamma_2+\gamma_3 cw_{a,t})\right)), \quad (27)$$

$$\gamma_0=1/(1+\exp\left(-\gamma_1\right)), \quad (28)$$

$$\gamma_h \sim \mathrm{MVN}(\hat{\gamma}_h, \Sigma_\gamma), \tag{39}$$
$$\hat{\gamma}_{h=1} = -4.276, \tag{30}$$
$$\hat{\gamma}_{h=2} = 0.0792, \tag{31}$$
$$\hat{\gamma}_{h=3} = 0.683, \tag{32}$$
$$\Sigma_\gamma = \begin{pmatrix} 0.214 & & \\ -0.003 & 8.758 \times 10^{-5} & \\ 0.002 & -0.001 & 0.074 \end{pmatrix} \tag{33}$$

Please note that the upper triangular area is omitted.

5. Catch in number by instar

Catch in weight was stratified as catch in number by instar using carapace width composition data and average weights by instar found in catches measured by the Fukushima Prefectural Fisheries Experimental Station (Current name: Fukushima Fisheries Resources Institute). However, actual measurement data is only available for 1999, 2003, and 2007, so years without data were supplemented with adjacent data (1999 was used for 1997 and 1998, 2003 was used for 2002, and 2007 was used for 2008 to 2010). No catch samples have been measured since 2011, so due to the low catch in weight, catch in number by instar was found using carapace width composition data from bottom-trawl surveys. Data for 2018 was taken from measurements of catch samples from a commissioned survey operated by offshore trawl fishermen in Fukushima. The following equations define the likelihood functions for the catch in weight section, with *c* indicating the observed catch in number by instar, and *C* indicating the estimated catch in number.

$$\ln(c_{a,u,t}) \sim \mathrm{Normal}(\ln(C_{a,u,t}), \tau^2_{a,u}), \tag{34}$$
$$C_{a,u=0,t} = N_{a,u=0,j=1,t} \exp(-M_t/6)\left(1 - F_{k=1,t}\right) w_{a,u=0,t}, \tag{35}$$
$$C_{a,u=1,t} = \sum_{j=2}^{3} N_{a,u=1,j,t} \exp(-M_t/6)\left(1 - F_{k,t}\right) w_{a,u=1,t}, \tag{36}$$

Both equations (35) and (36) were used for males, but only equation (36) was used for females because catch only included individual females which completed their terminal molt.

Estimated stock populations size by instar for each year are shown in Supplementary Figure 2-3 and Supplementary Table 2-2, and the residuals of standing stock based on bottom-trawl surveys and stock abundance estimated using JASAM are shown in Supplementary Figure 2-4. Furthermore, the results of retrospective analysis of stock abundance estimates and natural mortality coefficient M are shown in Supplementary Figure 2-5 and 2-6, respectively. As an indicator of retrospective bias, Mohn's rho (ρ, Mohn 1999) for abundance and M were calculated using equations (37) and (38), and the results were ρ_A = 11.6% and ρ_M = -21.3%, respectively.

$$\rho_A = \frac{1}{5}\sum_{i=1}^{5}\left(\frac{A_{T-i,R_i} - A_{T-i}}{A_{T-i}}\right) \times 100 \tag{37}$$

$$\rho_M = \frac{1}{5}\sum_{i=1}^{5}\left(\frac{M_{T-i,R_i} - M_{T-i}}{M_{T-i}}\right) \times 100 \tag{38}$$

In these equations, i = 1, 2, ... , 5 and T = 2020, and stock abundance estimated based on data from 1997 to T-i is shown as A_{T-i,R_i}, and M is shown as M_{T-i,R_i} ($R_i = R_1, ..., R_5$). In addition, the subscript letter R_i indicates how many years of data have been removed.

The following equations for carapace width - body weight relationships were used for every calculation process which converted stock population size into weight in this report (Kitagawa 2000). CW indicates carapace width (mm), and BW indicates body weight (g) (Supplementary Figure 2-1).

Male (immature) $BW = 7.943 \times 10^{-4} \times CW^{2.815}$

Male (mature) $BW = 4.954 \times 10^{-4} \times CW^{2.946}$

Female (immature) $BW = 9.616 \times 10^{-4} \times CW^{2.755}$

Male (mature) $BW = 3.556 \times 10^{-3} \times CW^{2.464}$

(2) Future Forecast Methods

Future forecasts for the 2021 to 2052 fishing seasons were calculated based on stock abundance by instar in the 2020 fishing season estimated in stock assessment reports, current natural mortality coefficient (M) (average value for 2018 to 2020), and current fishing pressure (F2018-2020). The settings of various parameters are shown in Supplementary Table 2-3. Forecasting future recruitment for the 2021 fishing season and after were calculated based on the hockey-stick model (a = 18.169, b = 259.85, SD = 0.275, rho = 0.861) proposed at the Research Agency Forum on Reference Points held in April 2020 (Morikawa et al. 2020). The data used to estimate the parameters of the stock-recruitment relationship model was SSB and recruitment based on stock assessments for 2019 (Shibata et al. 2020), and the optimization method was the least squares method. In addition, autocorrelation was considered regarding residuals in recruitment. Recruitment in future forecasts was predicted based on SSB in each annual fishing season using the stock-recruitment relationship model. Calculations were repeated 5,000 times assuming errors which follow log-normal distribution to account for uncertainty in recruitment. Catch in weight after the 2020 fishing season was calculated based on forecasted stock abundance and current fishing pressure (F2018-2020). For reference, calculations were also performed with fishing pressure set to zero after the 2021 fishing season. The population dynamics model used for the calculation is the same as shown in (1) Stock Calculation Methods.

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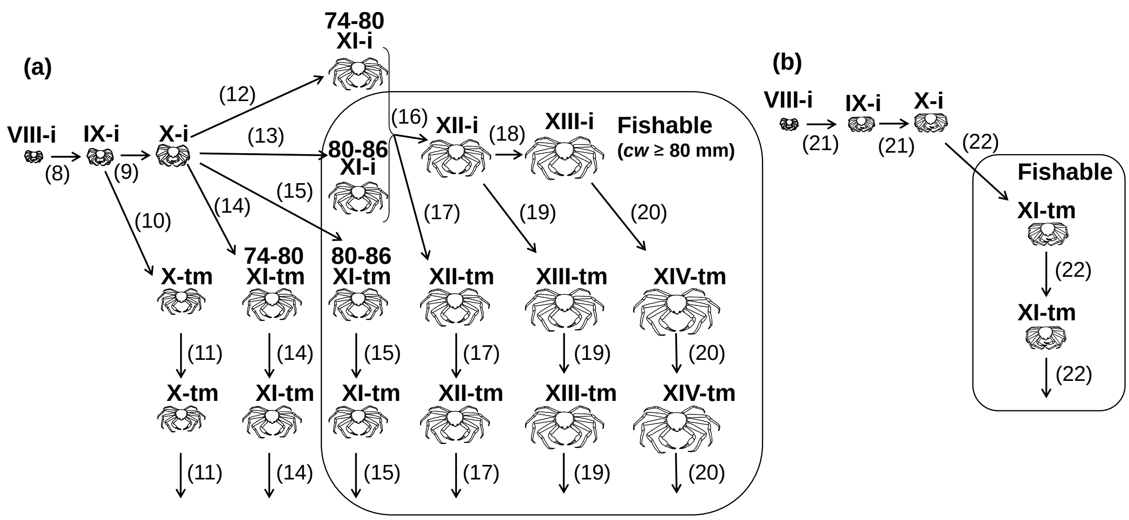
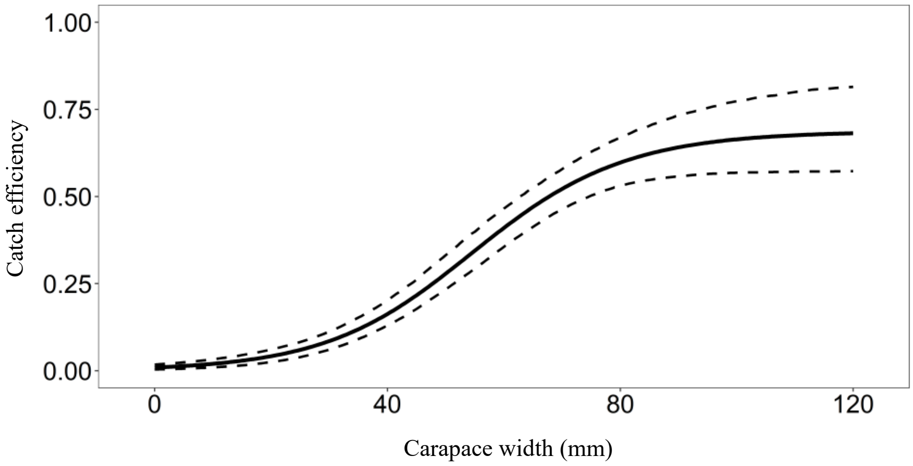
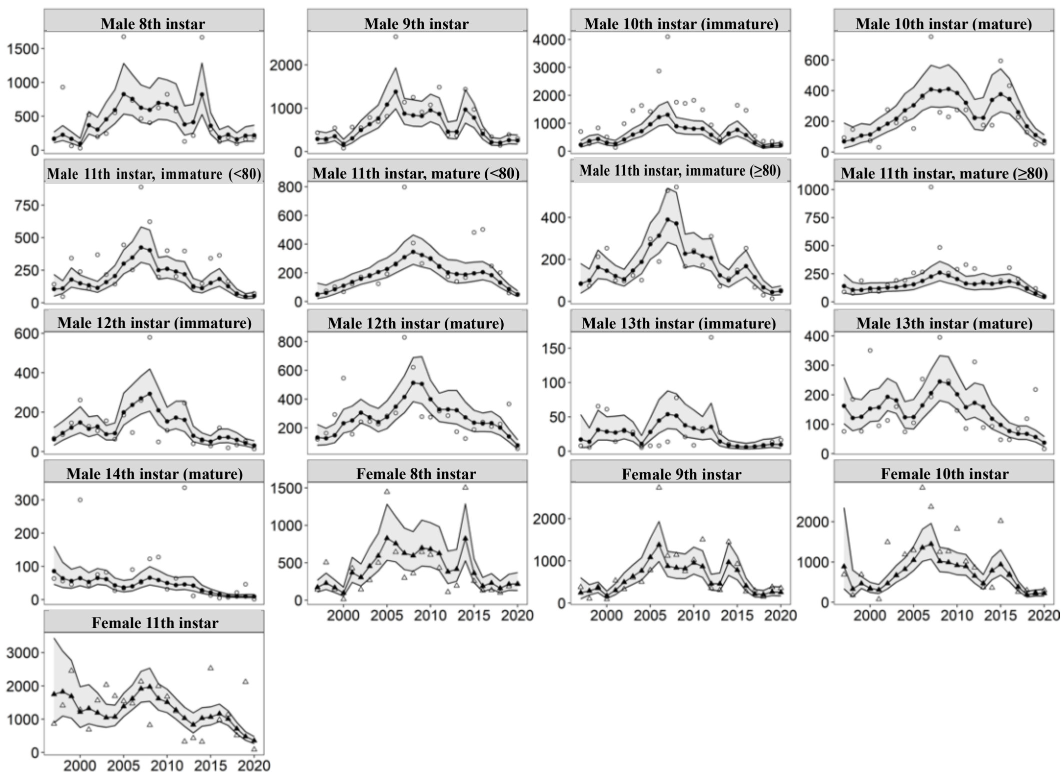


Supplementary Figure 2-1. Population dynamics model for snow crabs

In this figure, (a) and (b) represent the male and female population dynamics models, respectively. The numbers in parentheses in the figure refer to the equations in the main text of Appendix 2.



Supplementary Figure 2-2. Carapace width vs. catch efficiency

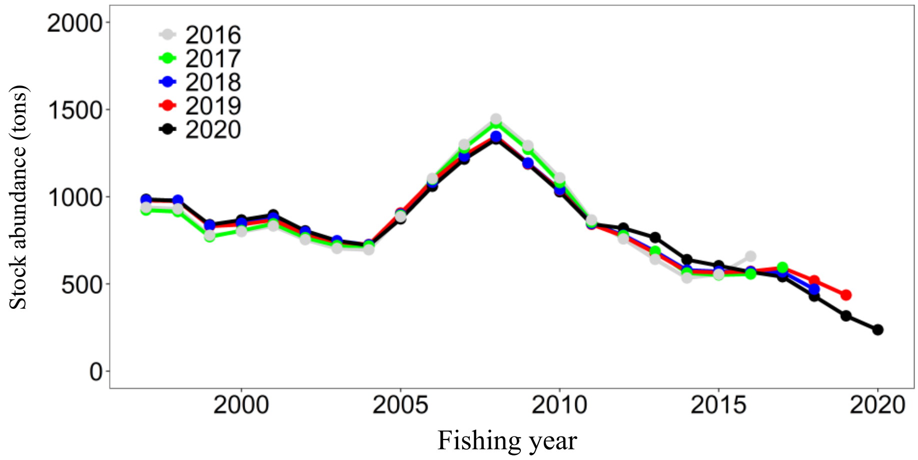


Supplementary Figure 2-3. Trends in stock population size by sex and by instar (no consideration of catch efficiency)

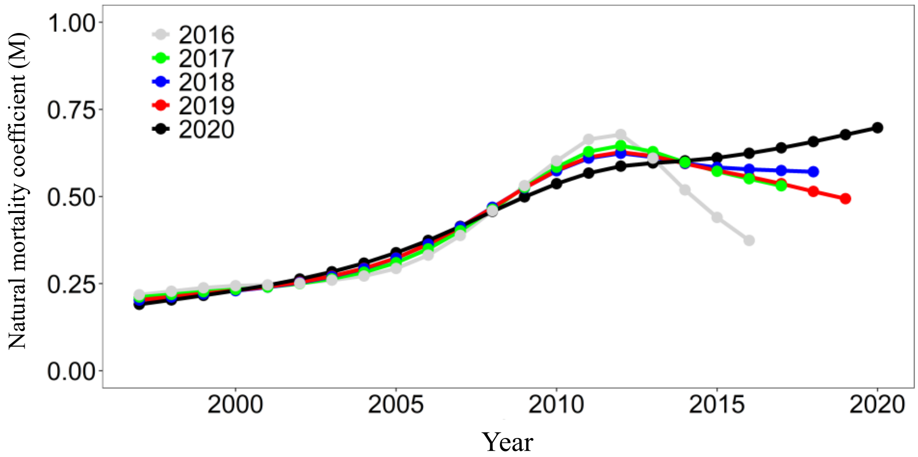
White dots indicate the stock population size based on bottom-trawl surveys, and black dots indicate stock population size based on JASAM estimates. The shaded area indicates the 95% confidence interval for estimated values for stock abundance.

Supplementary Figure 2-4. Residual plots ofstock population size by sex and by instar

These plots show residuals of stockpopulation size in JASAM estimates corresponding to stockpopulation size data from bottom-trawl surveys. The dotted line indicates zero, the vertical axis represents residuals, the dark and light shaded areas indicate the 80% points and 95% points, respectively, when a normal distribution is applied to the residuals.



Supplementary Figure 2-5. Retrospective analysis of JASAM estimates for stock abundance



Supplementary Figure 2-6. Retrospective analysis of JASAM estimates for M

Supplementary Table 2-1. Population size by instar from bottom-trawl surveys (no consideration of catch efficiency)

Instar	Sex	Maturity	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
8	M	IM	166	931	63	30	525	199	246	553	1,677	735	467	406
9	M	IM	434	266	546	79	565	548	784	693	816	2,652	1,140	1,255
10	M	IM	705	273	834	509	136	987	1,456	1,640	1,423	2,873	4,102	1,757
10	M	M	94	147	107	73	30	276	190	217	153	356	752	259
11	M	IM	142	47	343	239	108	369	216	143	445	252	889	623
11	M	M	47	75	102	69	123	171	184	124	192	260	798	408
11	M	IM	85	74	213	254	99	97	124	101	298	190	528	545
11	M	M	88	77	189	103	92	148	191	193	258	266	1,023	485
12	M	IM	68	86	146	262	129	106	156	63	185	97	260	579
12	M	M	122	164	293	546	156	242	244	228	283	304	829	621
13	M	IM	8	6	65	61	14	30	28	5	8	8	14	78
13	M	M	76	185	76	351	95	113	160	74	105	253	193	395
14	M	M	64	56	45	300	45	75	82	28	34	90	52	122
8	F	IM	144	505	145	14	427	144	268	501	1,446	643	299	359
9	F	IM	380	107	385	93	536	331	608	500	780	2,733	1,119	1,140
10	F	IM	689	177	686	332	77	1,494	667	1,184	1,289	2,844	2,368	1,249
11	F	M	861	1,413	2,455	1,286	688	1,566	2,031	1,695	1,542	1,472	2,130	822

Instar	Sex	Maturity	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
8	M	IM	625	826	581	130	216	1,668	311	127	188	97	160	191
9	M	IM	912	1,078	1,487	382	363	1,440	974	473	344	145	392	302
10	M	IM	1,716	1,822	1,485	942	466	610	1,646	1,467	546	360	351	293
10	M	M	229	275	275	221	175	175	595	432	227	128	49	56
11	M	IM	199	401	202	398	120	147	342	365	164	70	49	72
11	M	M	265	301	242	174	140	168	482	502	248	202	60	49
11	M	IM	166	243	172	310	72	108	149	254	67	30	14	52
11	M	M	255	290	331	296	178	161	192	303	204	123	119	51
12	M	IM	50	107	173	247	40	56	29	121	19	35	53	14
12	M	M	278	275	316	285	173	126	189	240	210	227	366	56
13	M	IM	21	9	33	166	27	10	0	0	0	7	13	16
13	M	M	247	146	86	312	89	93	48	47	84	119	218	17
14	M	M	128	32	64	337	11	25	13	5	7	21	46	1
8	F	IM	643	606	432	109	193	1,503	256	129	135	102	186	217
9	F	IM	756	1,022	1,507	354	308	1,449	926	277	301	151	382	356
10	F	IM	1,264	1,824	1,013	864	372	363	2,019	672	261	299	246	298
11	F	M	1,996	1,679	1,242	329	430	320	2,528	981	1,145	517	2,118	88

Supplementary Table 2-2. Population size by instar estimated by JASAM (no consideration of catch efficiency)

Instar	Sex	Maturity	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
8	M	IM	172	229	168	97	369	305	455	593	828	757	628	596
9	M	IM	292	290	353	177	305	497	633	765	1,085	1,380	877	837
10	M	IM	233	367	438	309	270	418	595	716	966	1,221	1,304	896
10	M	M	68	80	107	114	151	184	217	272	305	366	408	399
11	M	IM	105	110	179	150	134	114	158	206	300	348	425	404
11	M	M	52	61	86	110	137	160	178	206	227	263	310	347
11	M	IM	84	100	163	146	121	105	147	188	273	313	390	372
11	M	M	140	107	105	119	120	127	131	143	156	186	225	260
12	M	IM	63	95	122	148	116	127	89	93	200	237	270	294
12	M	M	133	128	149	233	251	306	274	240	275	347	415	513
13	M	IM	17	14	31	29	27	31	25	11	28	45	54	52
13	M	M	162	121	126	153	157	193	181	124	125	164	206	245
14	M	M	86	64	56	64	53	65	62	43	36	40	55	66
8	F	IM	172	229	168	97	369	305	455	593	828	757	628	596
9	F	IM	247	290	353	177	305	497	633	765	1,085	1,380	877	837
10	F	IM	886	330	468	348	309	470	674	823	1,047	1,357	1,448	1,019
11	F	M	1,749	1,827	1,688	1,217	1,326	1,195	1,049	1,071	1,384	1,617	1,919	1,974

Instar	Sex	Maturity	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
8	M	IM	699	681	626	381	415	823	362	189	231	160	214	219
9	M	IM	820	955	869	459	457	969	781	410	217	205	264	256
10	M	IM	840	807	804	587	365	638	767	578	311	161	195	211
10	M	M	411	384	321	225	223	340	377	345	260	167	110	72
11	M	IM	250	261	239	219	127	112	152	183	127	71	48	53
11	M	M	325	298	247	203	192	188	197	205	184	132	87	51
11	M	IM	227	236	217	207	124	101	138	168	115	66	44	48
11	M	M	234	203	163	157	169	160	173	183	163	117	76	44
12	M	IM	210	153	173	161	81	61	51	71	73	60	44	31
12	M	M	506	399	328	329	323	273	236	230	233	202	141	80
13	M	IM	38	34	29	36	14	9	7	6	7	9	10	10
13	M	M	239	202	158	173	159	119	98	77	68	67	57	38
14	M	M	59	50	44	46	42	29	22	16	11	10	10	9
8	F	IM	699	681	626	381	415	823	362	189	231	160	214	219
9	F	IM	820	955	869	459	457	969	781	410	217	205	264	256
10	F	IM	991	918	891	656	470	789	938	695	384	192	218	226
11	F	M	1,620	1,510	1,276	1,032	835	1,030	1,066	1,164	1,009	713	480	356

Supplementary Table 2-3. Parameters used for future forecast calculations

Instar	Natural mortality coefficient (Note)	Maturity Ratio	Average weight (g)	Current fishing pressure (F2018-2020)
8	0.677	0.0	—	—
9	0.677	0.0	—	—
10	0.677	0.0	—	—
11	0.677	1.0	132	0.022

Note: Natural mortality coefficient is current M (average value in 2018 to 2020).

Appendix 3 Summary and Results of Research Vessel Surveys

Survey name:Surveys for demersal fish stock abundance

Survey period: September 30 to November 25, 2020

Survey area and sites: Supplementary Figure 3-1

Bottom-trawl stock abundance surveys have been conducted since 1997, but since 2002, the number of survey sites has been increased and locations have been changed in order to improve the accuracy of stock abundance estimates. The current number and locations of survey sites have been used since 2004. From 1997 to 2003, stock abundance estimates were conducted by dividing the target ocean area into 4 North-South zones, and 8 depth zones at 100 m intervals, and stock abundance calculations were performed for a total of 32 layers. Since 2004, in addition to the 4 North-South zones, the primary distribution zone of snow crabs at 200 m to 500 m deep is divided into 50 m intervals, and calculations are performed for a total of 48 layers. In the 2012 survey, there was a layer in a Southern zone with only 1 survey site in the primary distribution zone of snow crabs, so the layer with only 1 site was integrated with the adjacent depth zone. In the 2015 survey, a high-density site was identified at a depth of 510 m in the E line (site name: E510), and the coefficient of variation (CV) was extremely high, so this site was separated into a single layer to calculate stock abundance (see the report for 2016).

(1) 2020 survey overview

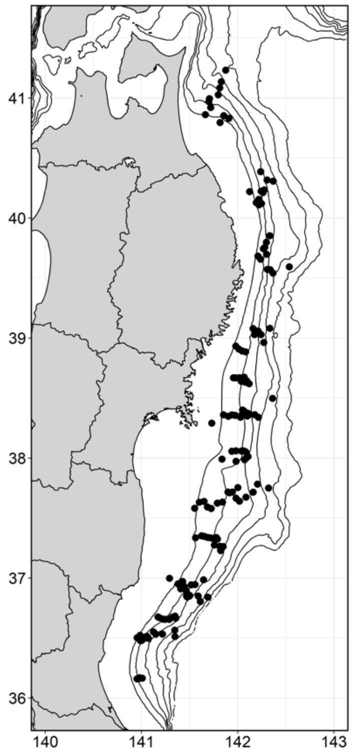
In 2020, a total of 150 bottom-trawl towing sites were planned at depths of 150 to 900 m, and surveys were conducted at 153 sites, including reserve sites (Supplementary Figure 3-1). Snow crabs were collected at a total of 88 sites, most of which were off the coast from Miyagi, Fukushima and Ibaraki Prefectures, the main fishing grounds for snow crabs, as in previous years.

(2) Annual changes in crab density

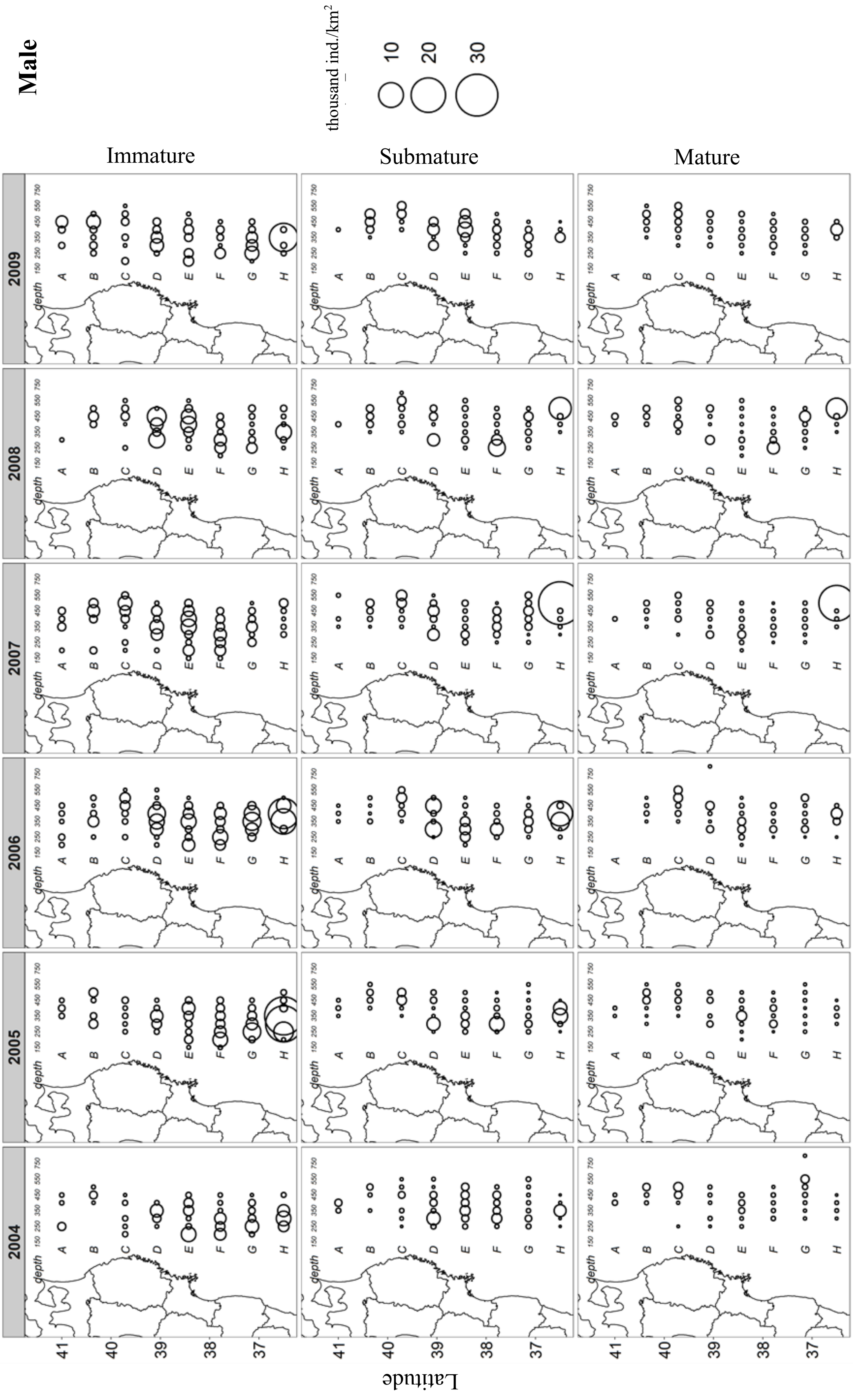
Trends in distribution since 2004, when the number of survey sites was expanded, were examined by sex and level of maturity (Supplementary Figure 3-2 to Supplementary Figure 3-7). Results showed that prior to 2010, both males and females demonstrated continuity in trends of distribution over time correlated with level of maturity, but since 2011, no clear continuity has been seen, and the situation has been characterized by the sudden appearance of high-density sites. In 2019, a site with high density of mature crabs appeared off the coast of Iwate, which had the highest density, for mature crabs only, for that year. However, no similar high density sites were found in 2020, and stock abundance based on surveys set the lowest.

In the 2000s, snow crabs were widely distributed throughout the Tohoku region, and a layer of high density appeared off Hitachi, the southern limit of this region, but in recent density has remained at low levels off the coast of southern Fukushima and Ibaraki.

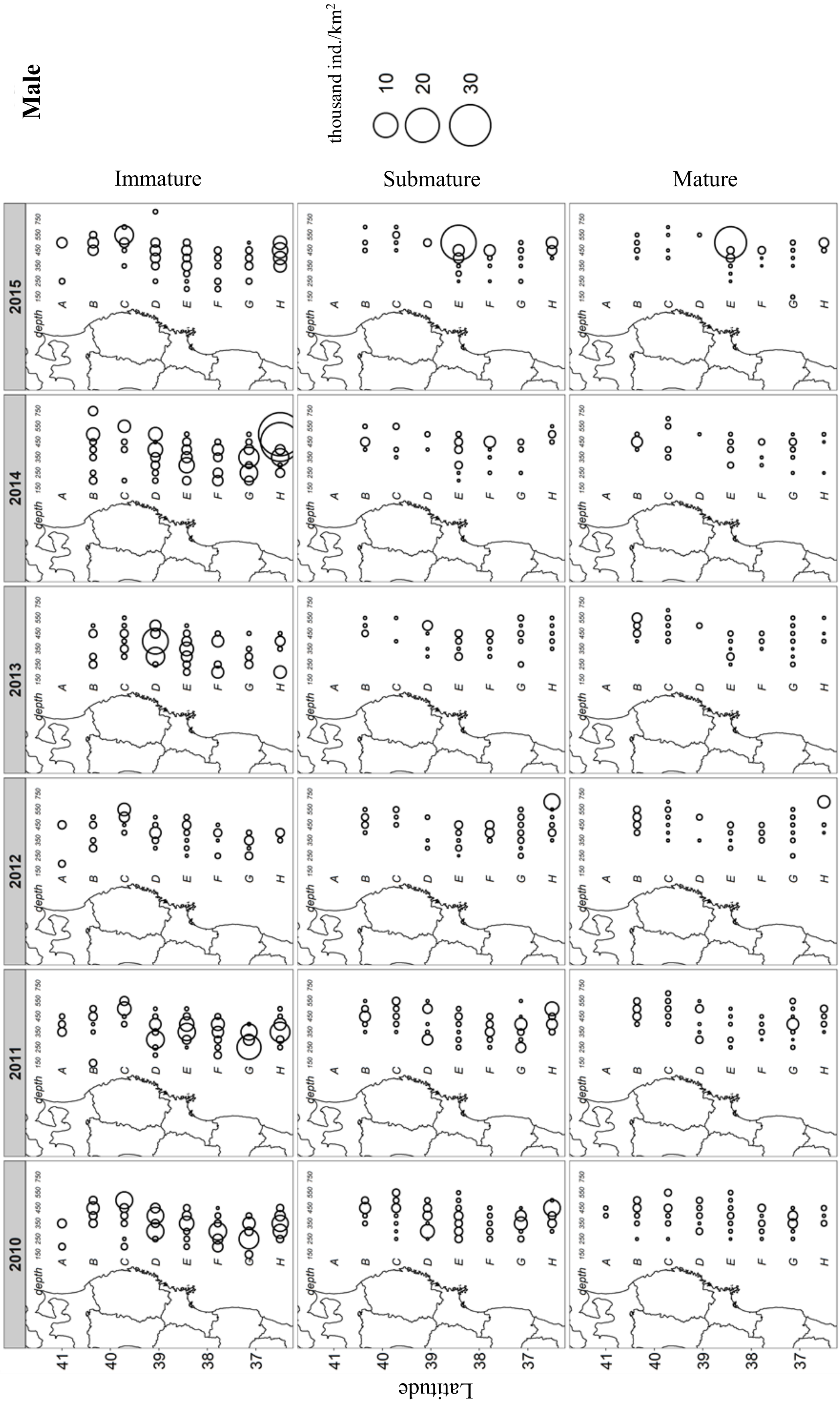
Observation of annual changes in density showed that distribution of mature crabs disappeared over a 2-to-3-year period, which leads us to believe that mature individuals which are considered fishable are only present for a few years, and the strength of recruitment has a huge impact on stock abundance.



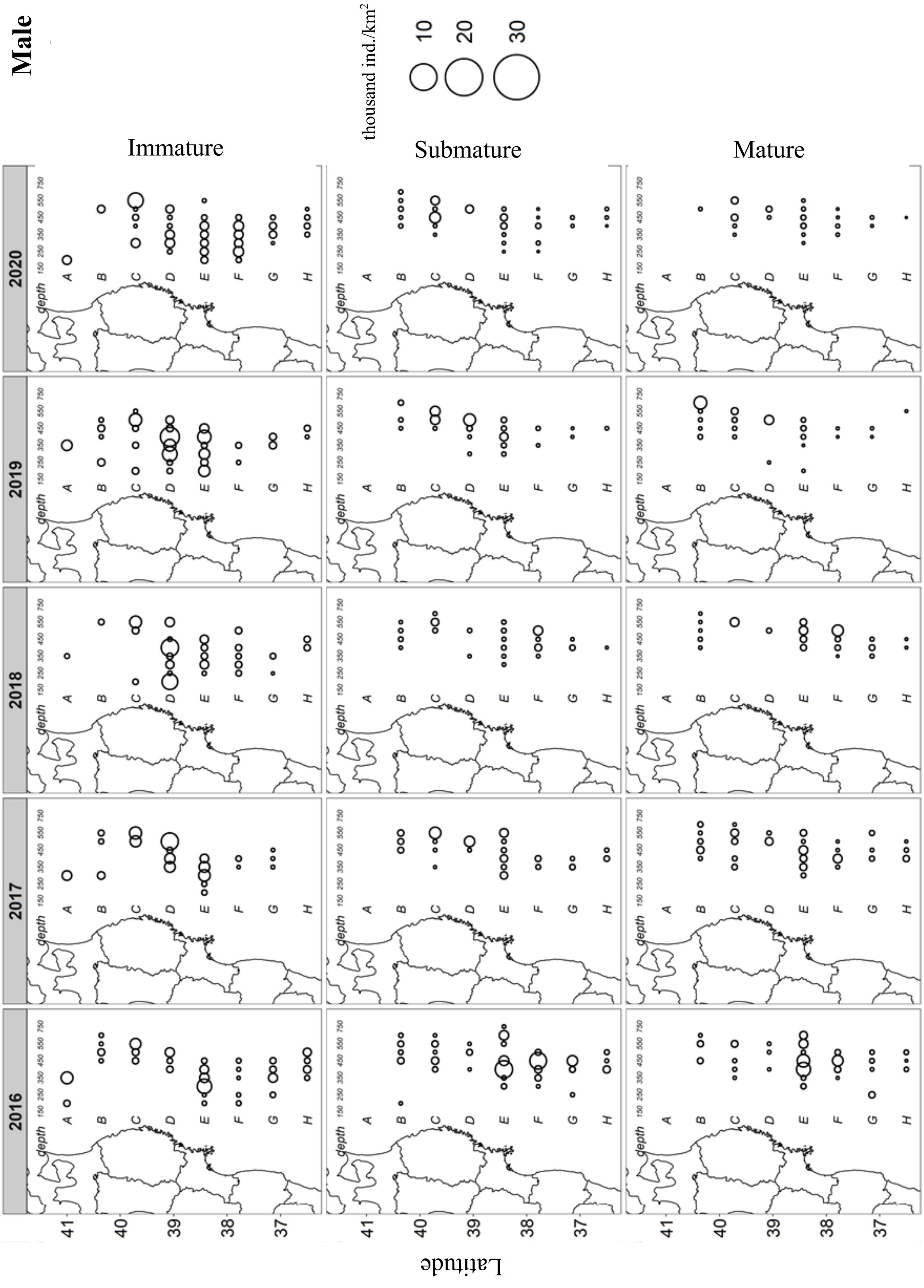
Supplementary Figure 3-1. Bottom-trawl survey sites in 2020



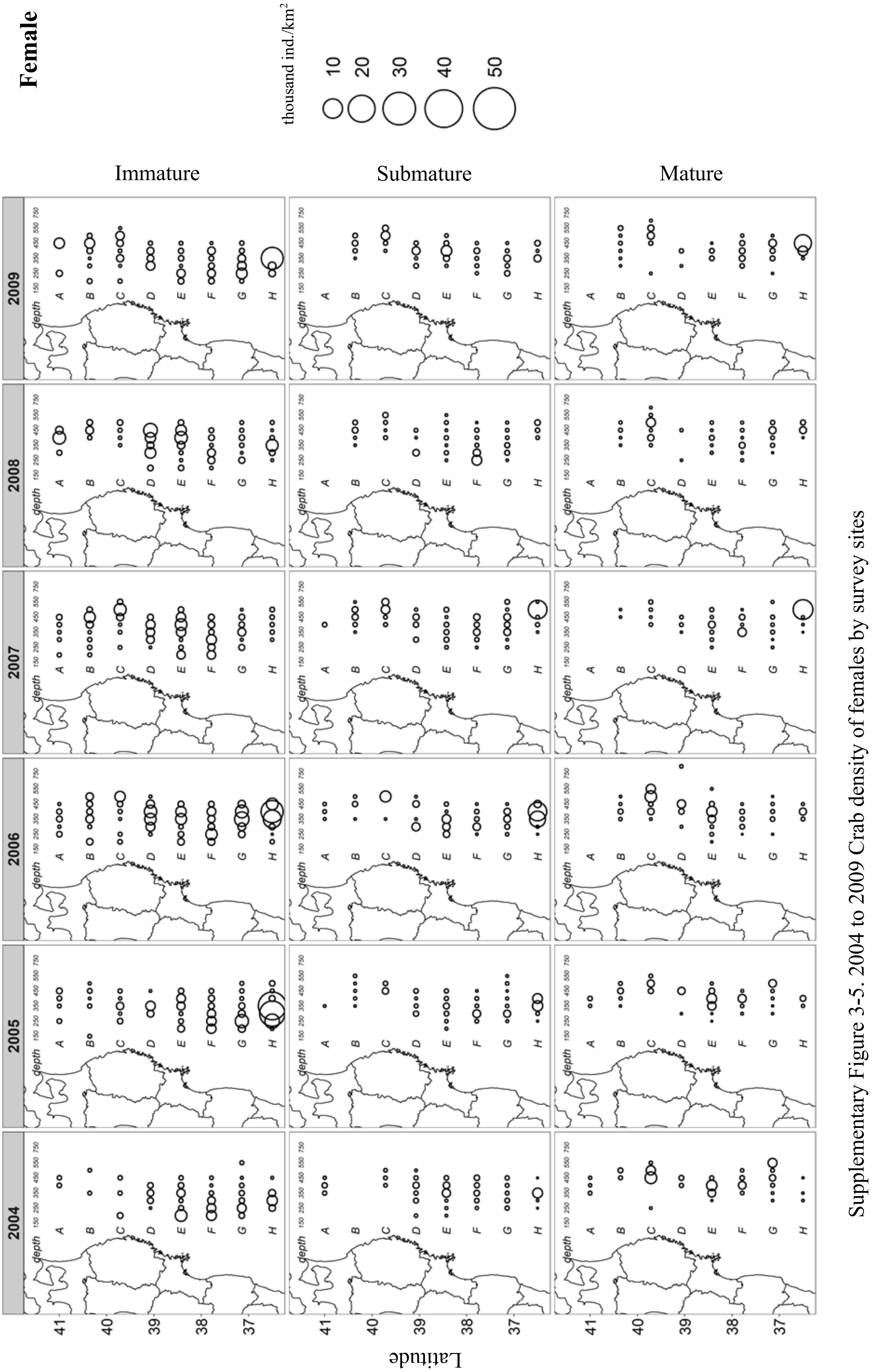
Supplementary Figure 3-2. 2004 to 2009 Crab density of males by survey sites



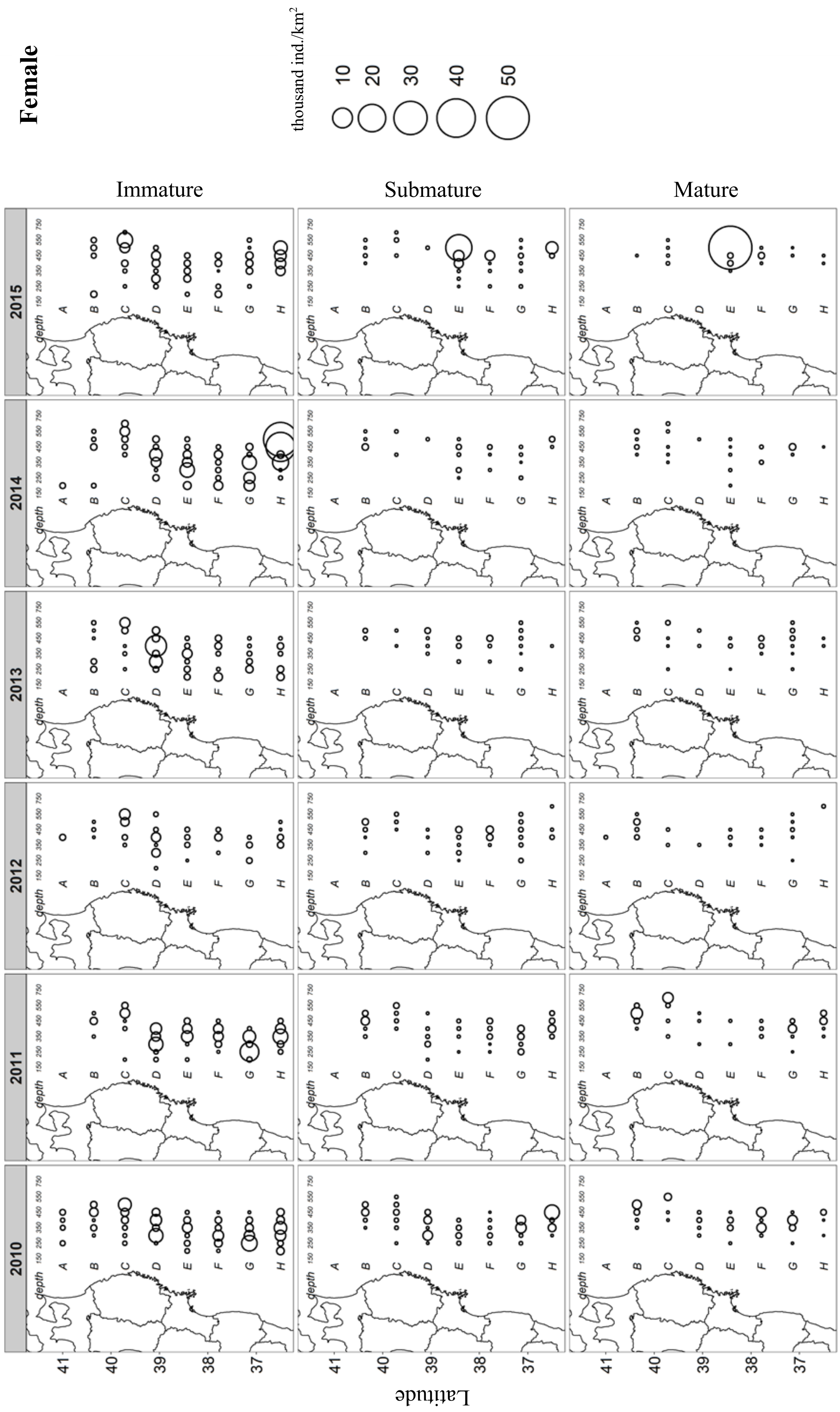
Supplementary Figure 3-3. 2010 to 2015 Crab density of males by survey sites



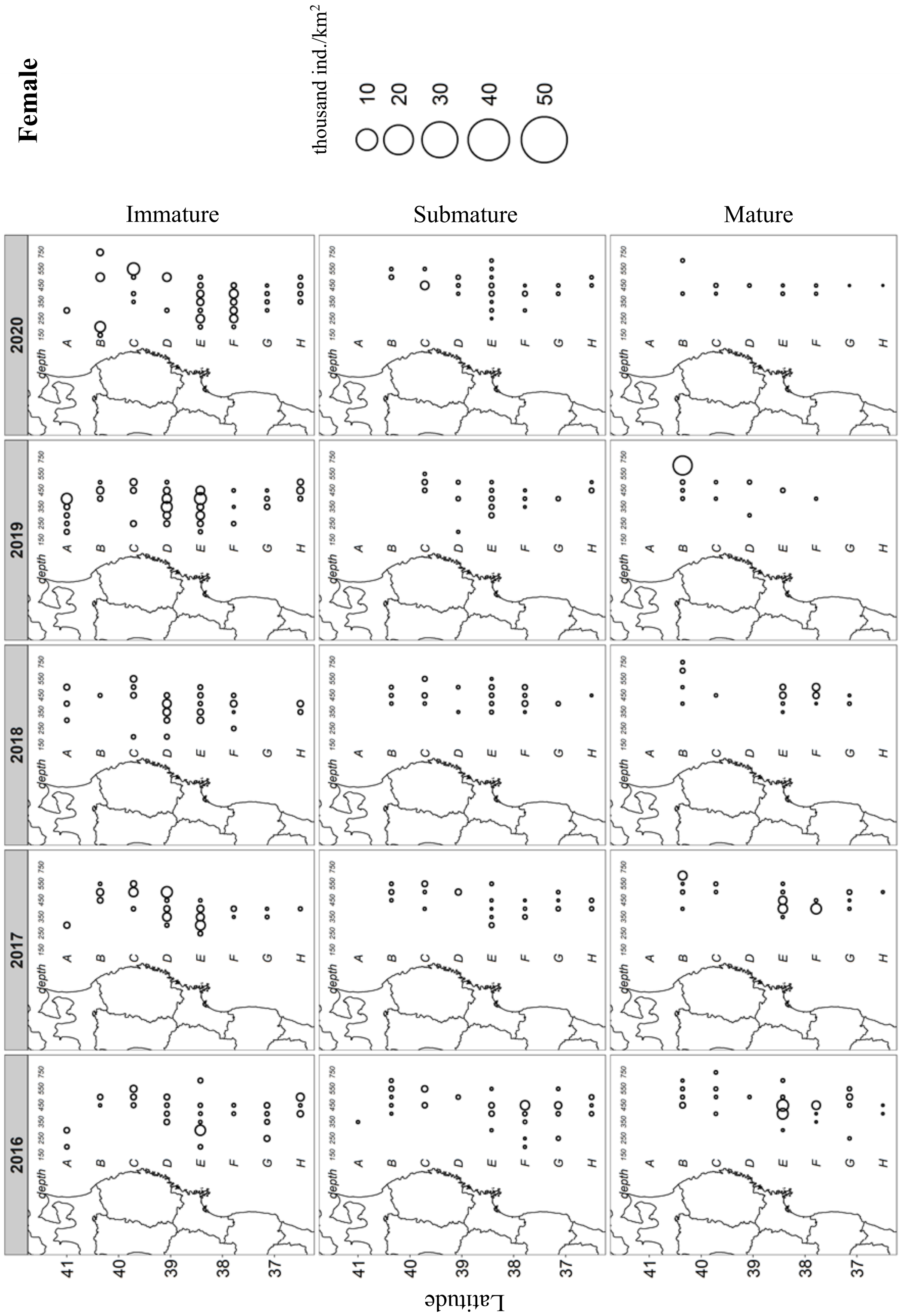
Supplementary Figure 3-4. 2016 to 2020 Crab density of males by survey sites



Supplementary Figure 3-5. 2004 to 2009 Crab density of females by survey sites



Supplementary Figure 3-6. 2010 to 2015 Crab density of females by survey sites



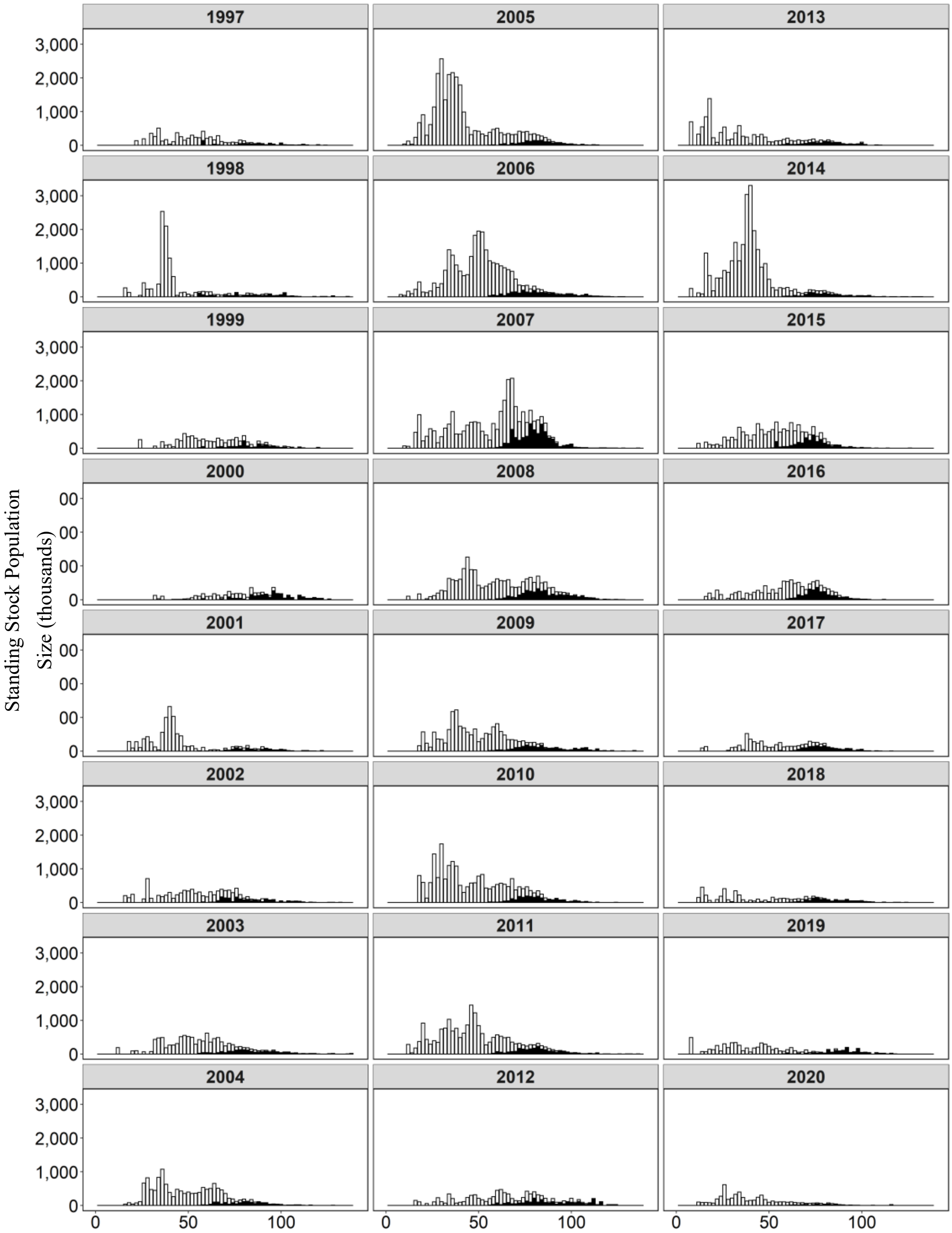
Supplementary Figure 3-7. 2016 to 2020 Crab density of females by survey sites

Appendix 4 Trends in Standing Stock Population Size by Carapace Width from Bottom-trawl Surveys

Using standing stock population size data from bottom-trawl surveys, and trends in carapace width composition are shown in Supplementary Figure 4-1 and Supplementary Figure 4-2. Carapace widths of males ranges from 10 mm to 130 mm, and the majority of fishable stock with a carapace width of 80 mm or more was individuals that had completed their terminal molts. In 1998, there were many individuals in the 38 mm carapace width group, but since then, the non-fishable standing stock population size with a carapace width of 30 mm to 70 mm has declined. In 2005, the non-fishable standing stock population size increased, and their growth led to an increase in fishable stock with a carapace width of 80 mm or more in 2007 and 2008. Immediately after the Earthquake in 2011, relatively large numbers of crabs in the 10th and 9th instar were found, which were expected to become fishable stock in 2012 and 2013, respectively. However, in 2013, fishable stock decreased despite reduced catch due to the impact of the Earthquake.

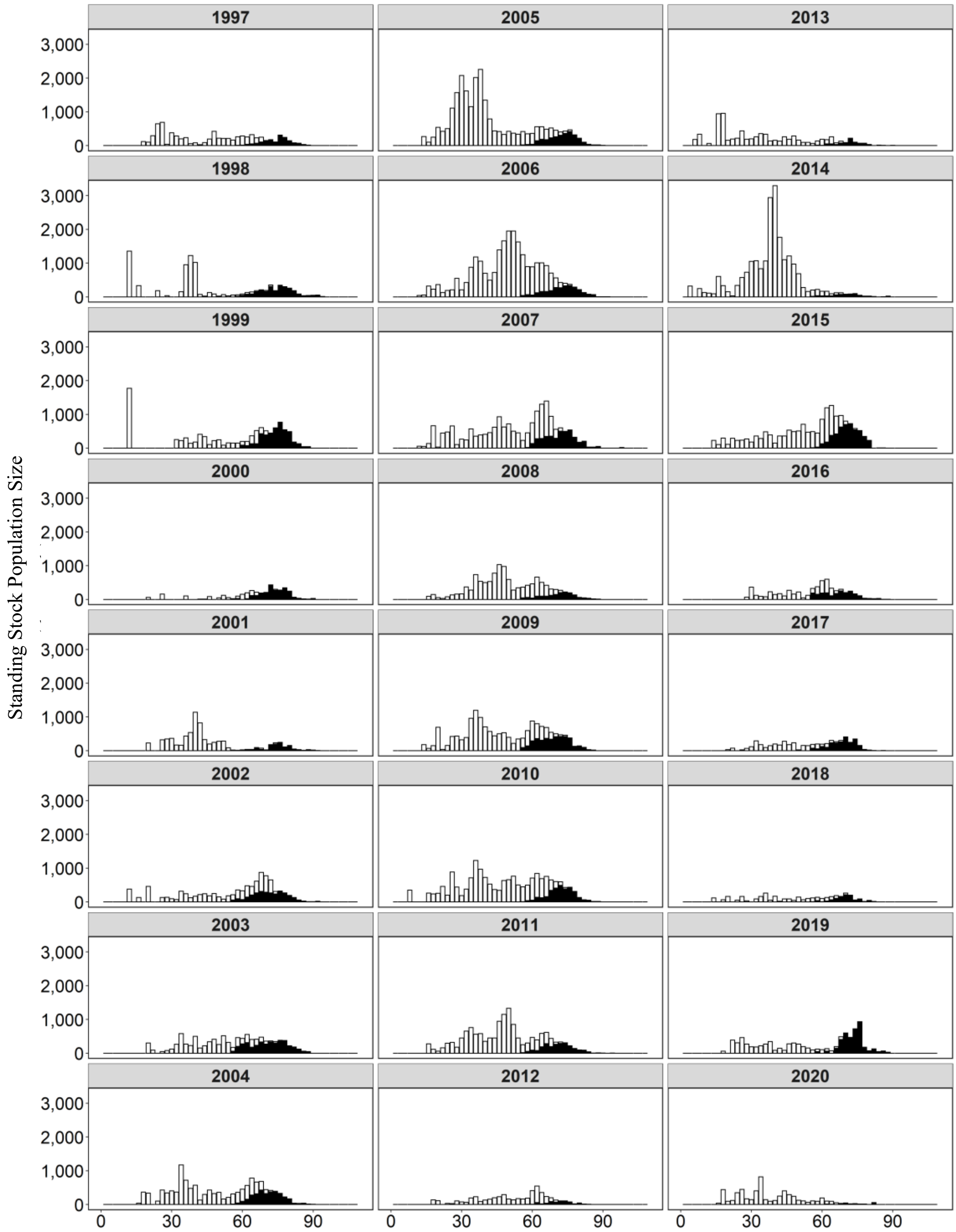
Carapace width composition in 2012 and 2013 showed few individuals with a carapace width of less than 80 mm in both years. In 2012, there were many individuals with a carapace width of 100 mm or more, but these large individuals were not seen in 2013. The number of small individuals with a carapace width of less than 50 mm increased in 2014, and the number of mature individuals increased in 2015 and 2016. In 2017, the number of individuals measuring 100 mm or more increased compared to 2015 and 2016. In 2018, the number of individuals with 100 mm or more also appeared compared to the previous year, but there was an overall decrease in stock population size. In 2019, the number of mature individuals with a carapace width of 90 mm or more increased, in addition to an increase in the number of individuals with a carapace width of 60 mm or less, compared to 2018. On the other hand, in 2020, there were significantly fewer mature individuals and also fewer immature individuals.

In females, the majority of individuals with a carapace width of 76 mm or more were mature, and were considered to be fishable stock. Similar to males, females also had a large non-fishable standing stock population size with a carapace width of 60 mm or less in 2005 and 2006, and their growth led to an increase in fishable stock in 2007. However, in 2008, the fishable stock population size decreased to approx. half of levels in 2007. In 2009, the fishable stock recovered to levels seen in 2002 to 2007, which leads us to believe that the low fishable stock population size in 2008 was probably underestimated. In 2011, the fishable stock population size decreased slightly, then declined even more in 2012 and 2013. In 2014, the fishable stock population size continued to be low, but similar to males, the number of small individuals with a carapace width of 50 mm or less increased. Subsequently, the fishable stock size increased in 2015, but in 2016 and 2017 it decreased to same levels as 2011. In 2019, the catch target stock population size was remarkably high, but then it declined sharply in 2020. If we only look at fishable stock, then its in 2020 was lower than in 2018, and it was the lowest stock population size since surveys began in 1997.



Supplementary Figure 4-1. Male standing stock population size by carapace width

The horizontal axis represents carapace width (mm), immature individuals are shown in white, and mature individuals are shown in black. Mature and immature are defined based on completion of the terminal molt.



Supplementary Figure 4-2 Female standing stock population size by carapace width

The horizontal axis represents carapace width (mm), immature individuals are shown in white, and mature individuals are shown in black. Mature and immature are defined based on completion of the terminal molt.

Appendix 5 Instar Composition in Catches

Catch in number by instar for males was estimated based on catch in weight data tracked by prefectures since the 1997 fishing season and carapace width composition of catches measured in the market surveys conducted by Fukushima since 1999 (Supplementary Table 5-1). Because carapace width composition data was missing for some years, catch in number by instar was estimated by supplementing with adjacent carapace width composition data. Specifically, 1999 was used for 1997 and 1998, the average of 2001 and 2003 was used for 2002, and 2007 was used for 2008 and 2010. In addition, because market measurements have not been conducted since the 2011 fishing season, with an exemption in the 2018 fishing season, catch in number by instar was calculated by substituting catch in weight by instar data from bottom-trawl surveys. Data for 2018 was taken from carapace width composition from a commissioned survey operated by offshore trawl fishermen in Fukushima.

Supplementary Table 5-1. Catch of males by instar (tons)

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
8th instar, pre terminal molt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9th instar, pre terminal molt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10th instar, pre terminal molt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10th instar, post terminal molt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11th instar, pre terminal molt (CW of 80 mm or less)	11.9	6.1	4.3	0.6	0.0	1.0	2.8	0.0	0.0	0.8	0.9	1.6
11th instar, post terminal molt (CW of 80 mm or less)	7.1	3.7	2.6	0.5	0.0	0.6	1.7	0.0	0.0	0.9	0.3	0.5
11th instar, pre terminal molt (CW of 80 mm or more)	13.5	7.0	4.9	3.0	2.2	5.0	10.6	1.5	5.7	7.7	3.2	5.6
11th instar, post terminal molt (CW of 80 mm or more)	12.9	6.7	4.7	6.5	10.4	9.9	9.3	9.1	11.2	10.5	6.4	11.2
12th instar, pre terminal molt	10.5	5.4	3.8	1.9	5.1	11.6	24.5	1.7	9.8	9.0	6.7	11.9
12th instar, post terminal molt	17.4	9.0	6.4	17.1	17.8	21.4	28.9	15.1	10.3	20.4	27.0	47.7
13th instar, pre terminal molt	9.7	5.0	3.5	0.3	1.0	1.7	2.9	0.4	1.7	4.6	2.0	3.5
13th instar, post terminal molt	27.2	14.1	9.9	12.8	20.5	22.2	26.1	8.8	6.0	17.4	20.5	36.1
14th instar, post terminal molt	37.4	19.4	13.7	0.9	4.4	6.8	11.4	7.2	8.6	6.2	8.8	15.5
Total	147.6	76.4	53.9	43.6	61.4	80.2	118.4	43.7	53.4	77.6	75.6	133.5

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
8th instar, pre terminal molt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9th instar, pre terminal molt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10th instar, pre terminal molt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10th instar, post terminal molt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11th instar, pre terminal molt (CW of 80 mm or less)	1.7	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11th instar, post terminal molt (CW of 80 mm or less)	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
11th instar, pre terminal molt (CW of 80 mm or more)	6.0	3.8	0.0	0.1	0.1	0.0	0.8	2.2	0.7	0.0	0.0	1.3
11th instar, post terminal molt (CW of 80 mm or more)	12.0	7.7	0.1	0.1	0.3	0.1	1.2	2.8	2.5	0.2	0.4	1.3
12th instar, pre terminal molt	12.6	8.1	0.0	0.1	0.1	0.0	0.2	1.2	0.3	0.0	0.2	0.4
12th instar, post terminal molt	50.8	32.5	0.1	0.2	0.3	0.1	1.5	2.8	3.2	0.4	1.7	1.9
13th instar, pre terminal molt	3.7	2.4	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	1.0
13th instar, post terminal molt	38.5	24.6	0.0	0.2	0.2	0.1	0.5	0.7	1.7	0.4	1.3	0.8
14th instar, post terminal molt	16.5	10.6	0.0	0.4	0.0	0.0	0.2	0.1	0.2	0.1	0.4	0.1
Total	142.4	91.0	0.3	1.3	1.1	0.3	4.5	9.7	8.6	1.2	4.2	6.7

Appendix 6 Investigation of Causes of Decline in this Stock

Stock abundance and SSB of this stock are in trends of decline despite continued low fishing pressure following the Earthquake. However, the cause of this has not yet been identified at this time.

Recent changes in habitat include a trend of rising yearly average bottom water temperatures in all prefectures from Miyagi, Fukushima, and Ibaraki. In particular, it has been revealed that the bottom water temperature in Miyagi and Ibaraki reached 7 °C to 8 °C in November and December in some years (Shibata et al. 2021). Foyle et al. (1989) reported that when water temperature is 7 °C or higher, energy consumed internally exceeds the energy absorbed from outside, which makes it impossible for snow crabs to thrive in that water temperature range from an energy balance perspective. Based on this, Shibata et al. (2021) pointed out that the increase bottom water temperature may be one of the reasons for the increase in M.

In order to understand trends in bottom water temperature in the Tohoku region, we extracted the water temperature information at the maximum observation depth and at relevant sites from data of ocean observations conducted by fishery experimental stations in Miyagi, Fukushima, and Ibaraki, and the Japan Fisheries Research and Education Agency. When using this extracted water temperature data, we selected bottom water temperature according to the following: temperature measured within 10 m above the ocean floor at sites in depths of 100 m or shallower, and temperature measured at the maximum observation depth if the difference between the observation depth and the true ocean depth is less than 10% at sites in depths of 100 m or more. Measured data were analyzed using flexible Gaussian filter (Shimizu and Ito, 1996), recorded by time, distance, and depth, and results were weighted and meshed (5 minutes by 5 minutes) and maintained as monthly data. The depth range was divided into two zones: the 300 m to 400 m zone inhabited by relatively small snow crabs, and the 400 m to 500 m zone inhabited by large snow crabs. In addition to the annual average, the average bottom water temperatures in November and December, when the southern limit of the distribution off Ibaraki Prefecture is at its highest, were extracted and organized (Supplementary Figure 6-1).

Results showed a trend of rising yearly average bottom water temperature since 2006, with yearly average temperature reaching 6.6 °C in the 300 m to 400 m depth zone, and 4.8 °C in the 400 m to 500 m depth zone, in all 3 prefectures in 2015. After that, it showed a declining trend, reaching 5.2 °C in the 300 m to 400 m depth zone and 4.1 °C in the 400 m to 500 m depth zone in 2020. This fluctuation is similar to trends in M, which was already rising prior to the Earthquake, but it is not completely consistent. The relationship between bottom water temperature and M demands further investigation.

Other possible causes of stock decline include an increase in terminal molt rate, changes in the habitat other than bottom water temperature, or changes in the ecosystem balance. The terminal molt rate of this stock was estimated using JASAM, and results showed an estimated rise in terminal molt rate since the 1997 fishing season (Supplementary Table 6-1). Furthermore, analysis of the feeding habits of Pacific cod suggests that predation has a not insignificant impact on snow crab stocks (Ito et al. 2014). However, none of these factors have been identified as the cause of the decline in this stock, so further research is needed.

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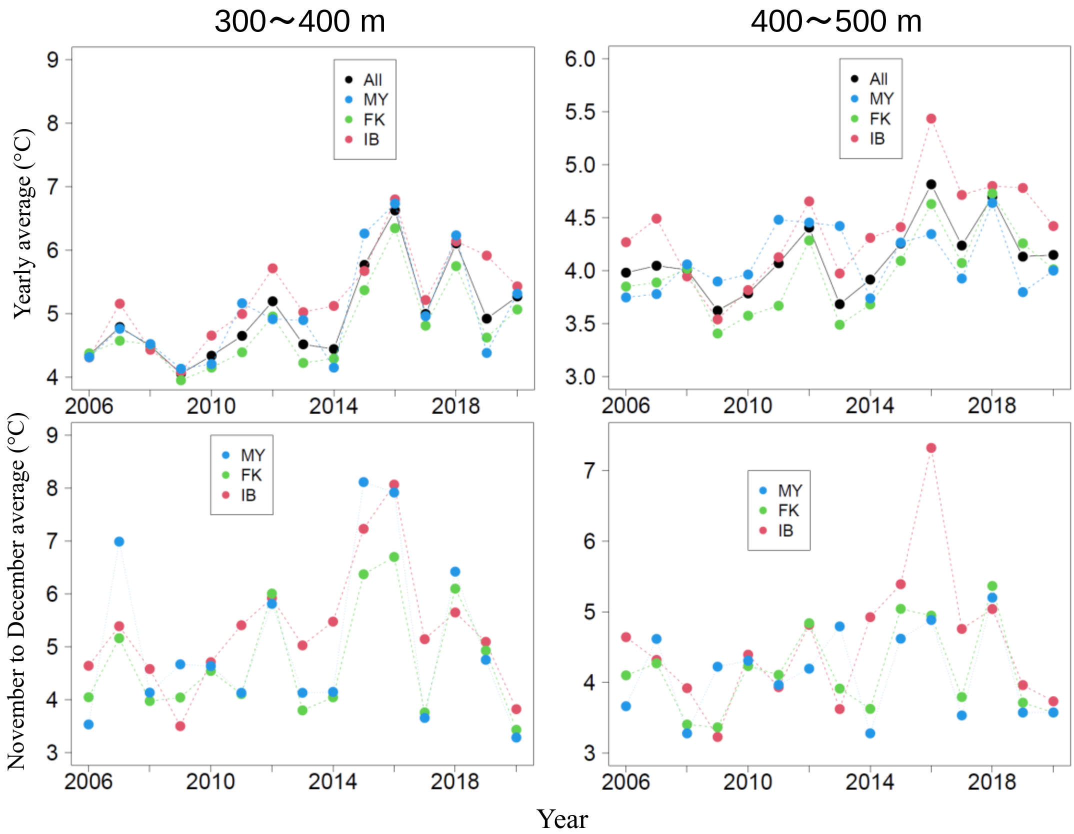

Supplementary Figure 6-1. Bottom water temperature of Tohoku prefectures (2006 to 2019)

All indicates the average of all prefectures (black), MY indicates offshore Miyagi (blue), FK indicates offshore Fukushima (green), and IB indicates offshore Ibaraki (red).

Supplementary Table 6-1. Terminal molt rate estimated by JASAM

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
9th instar	0.06	0.06	0.11	0.13	0.11	0.12	0.13	0.08	0.10	0.10	0.12	0.15
10th instar	0.14	0.15	0.25	0.27	0.25	0.26	0.28	0.18	0.23	0.22	0.26	0.32
11th instar	0.31	0.32	0.47	0.50	0.46	0.48	0.51	0.37	0.43	0.43	0.48	0.55
12th instar	0.54	0.55	0.70	0.72	0.69	0.70	0.73	0.60	0.67	0.66	0.71	0.76

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
9th instar	0.12	0.10	0.11	0.22	0.19	0.18	0.17	0.19	0.16	0.11	0.06	0.10
10th instar	0.26	0.22	0.24	0.43	0.38	0.37	0.35	0.38	0.34	0.24	0.15	0.23
11th instar	0.48	0.43	0.45	0.66	0.62	0.60	0.58	0.62	0.57	0.45	0.32	0.44
12th instar	0.71	0.66	0.68	0.84	0.81	0.80	0.78	0.81	0.78	0.68	0.55	0.68