Abstract.—A fishery for snow crab, *Chionoecetes opilio*, began in 1979 in a shallow water (<200 m) area off the Avalon Peninsula of southeastern Newfoundland and developed rapidly with landings peaking at 8609 metric tons (t) in 1981. Landings began to decline in 1982, and dropped to 74 t in 1985. This fishery collapse coincided with similar declines in catch per unit of effort (CPUE) and abundance of newly molted male snow crab. In Bonavista Bay, a deep water (>200 m) fishing area north of the Avalon Peninsula, CPUE declined less and the proportion of newly molted male snow crab remained relatively constant during the same period. Coincident with the decline of the Avalon Peninsula fishery was a pronounced drop in mean bottom temperature on the commercial fishing grounds, from −0.6° C to −1.4°C, a phenomenon not observed in Bonavista Bay. This decline in water temperature appears to have been the cause of the fishery collapse because temperatures became low enough to interrupt the molting cycle of snow crab off the Avalon Peninsula. If the potential impact of the lower water temperatures and subsequent long-term cessation of growth and recruitment within the snow crab population had been recognized, the available pool of commercial-sized crab could have been harvested more slowly over a period of years to lessen the disruption of the fishery.

Manuscript accepted 18 October 1993
Fishery Bulletin 92: 412–419.

A snow crab, *Chionoecetes opilio* (Decapoda, Majidae), fishery collapse in Newfoundland

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The Newfoundland snow crab, *Chionoecetes opilio*, fishery began in 1968, and until 1978 was confined to deep water (>220 m) bays and areas within 30 km of the coast. In 1978, fishing effort in offshore areas east of the Avalon Peninsula (Fig. 1) increased markedly, resulting in peak landings in 1981 (Fig. 2) of 8609 t (Taylor and O'Keefe[1]).

The Canadian Atlantic Fisheries Scientific Advisory Committee (CAFSAC) recommended that annual exploitation rates for commercially harvested snow crab stocks not exceed 50–60% of annual productivity in order to prevent overexploitation (Anon.[2]). The Committee adopted this guideline because the fishery targets males only and most males have an opportunity to mate at least once before reaching the minimum legal size, thereby ensuring adequate recruitment into the fishery and the reproductive integrity of the populations. However, should there be a recruitment failure, the reproductive potential is maintained by sublegal sexually mature males in the population and females that can produce at least two clutches of viable eggs from one copulation using stored sperm (Paul, 1984).

The fishery occurs from April until November each year. Typically, catch per unit of effort (CPUE) declines throughout the fishing season until July and August when a high level of molting activity results in an increased abundance of newly molted recruits. As fishermen are discouraged by processors from landing these low-yield soft-shelled crabs, new-shelled animals of legal size (≥95 mm carapace width (CW)) generally enter the fishery in the following spring. Their recruitment is evident by high CPUE values at the beginning of the next fishing season (Taylor and O'Keefe[1]).

Between 1979 and 1982, exploitation rates off the Avalon Peninsula remained within recommended levels, but beginning in 1982 catch rates declined rapidly until 1984 when fishing became uneconomical (Taylor and O'Keefe[3]). Other areas in Newfoundland, such as Bonavista Bay (Fig. 1), have consistently had exploitation rates in excess of recommended levels and consequently have experienced reductions in catch rates. However, the

[1] Taylor, D. M., and P. G. O'Keefe. 1984a. Assessment of Newfoundland snow crab (*Chionoecetes opilio*) stocks, 1982. Can. Atl. Fish. Sci. Advis. Comm. CAFSAC Res. Doc. 84/13, Dartmouth, Nova Scotia, 35 p.

[2] Anonymous, 1981. Advice on some invertebrate and marine plant stocks. Can. Atl. Fish. Sci. Advis. Comm. CAFSAC Advisory Document 81/1, Dartmouth, Nova Scotia, 6 p.

[3] Taylor, D. M., and P. G. O'Keefe. 1986. Analysis of the snow crab, *Chionoecetes opilio*, fishery in Newfoundland for 1985. Can. Atl. Fish. Sci. Advis. Comm. CAFSAC Res. Doc. 86/57, Dartmouth, Nova Scotia, 24 p.

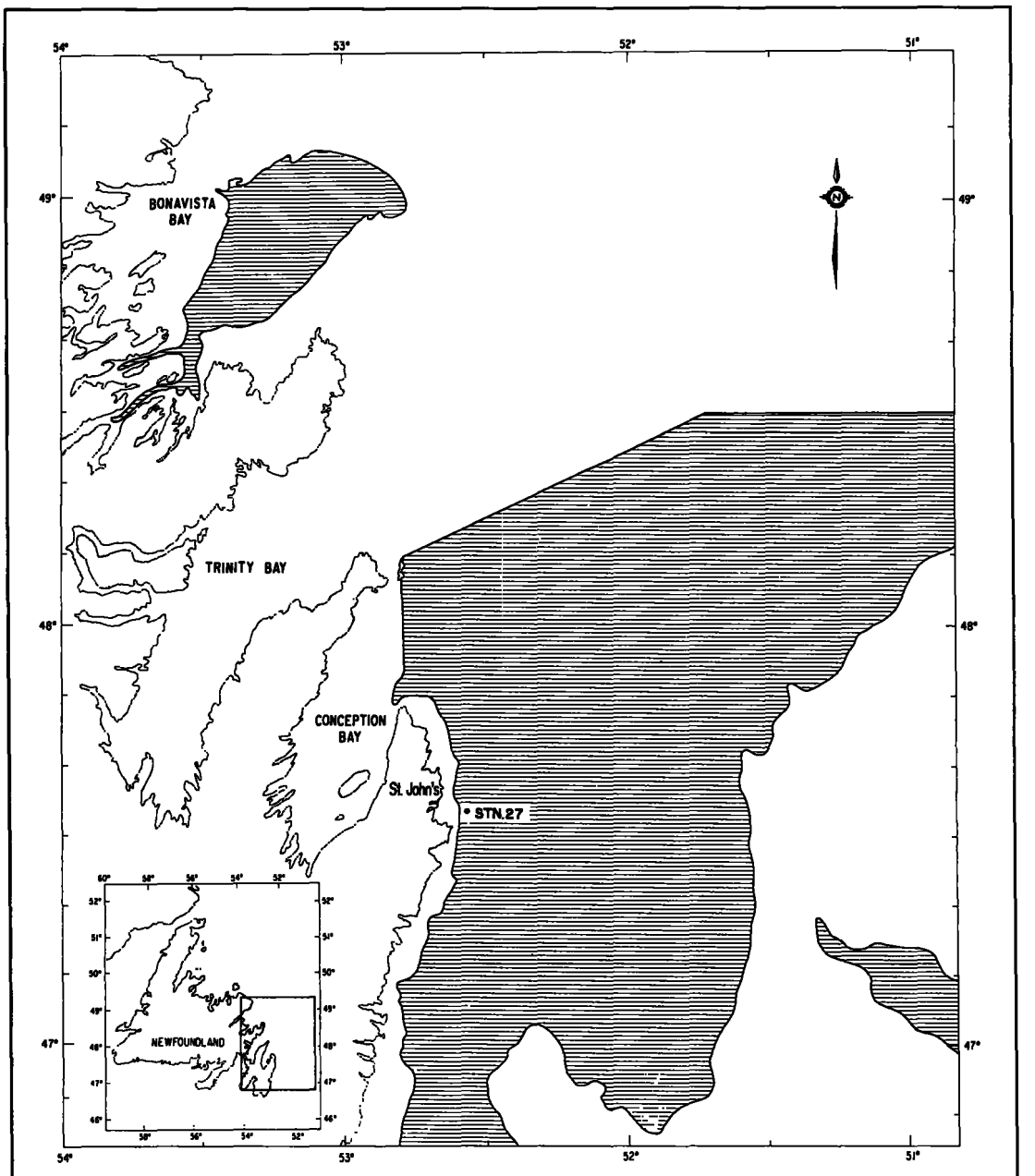

Figure 1
Offshore Avalon Peninsula and Bonavista Bay, Newfoundland, *Chionoecetes opilio* fishing grounds.

magnitude of the collapse in catch rates and landings off the Avalon Peninsula is unprecedented.

This paper examines biological data, fishermen's log returns, and temperature records from the Avalon Peninsula in comparison with similar data from Bonavista Bay in an attempt to describe possible reasons for this collapse.

Materials and methods

A total of 27 spring and fall cruises were conducted on the commercial fishing grounds off the Avalon Peninsula and in Bonavista Bay (Fig. 1) during 1979–88 to monitor population characteristics and catch rates. Fishing stations were selected randomly and strati-

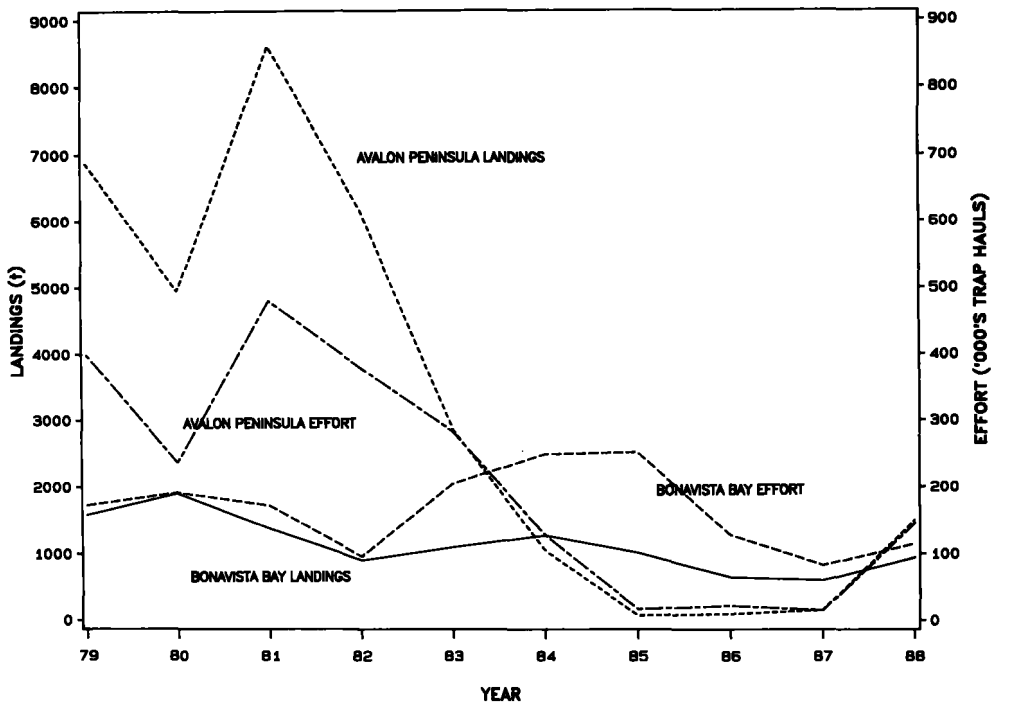

Figure 2

Summary of annual commercial landings and fishing effort for *Chionoecetes opilio* from offshore Avalon Peninsula and Bonavista Bay, Newfoundland.

fied by depth. Japanese-style conical traps baited with approximately two kg of northern shortfin squid, *Illex illecebrosus*, or with a mixture of squid and Atlantic mackerel, *Scomber scombrus*, and set in longline fleets of 12 were used to catch crabs. Although an attempt was made to duplicate the methodology employed by fishermen, space limitations onboard the research vessels restricted fleets of traps to 12 rather than the 50–70 used in commercial fishing. Weather permitting, traps were hauled after a 24–hour soak.

Crabs were removed from the traps, carapace width (CW) measured to the nearest 1 mm and shell condition determined. Three shell condition classes were used, based upon the following criteria described by Miller and O'Keefe (1981) and modified by Taylor et al. (1989):

Soft Shell (1) Carapace is brightly colored and free of epibiotic growth. Ventrally the crab is off-white to cream in color. Chelae bend, break, or crack with slight pressure. Bright iridescence present on dorsal margin of chelae. Animals within this category are considered as having molted not more than 90 days prior to capture.

New/Hard (2) Carapace is duller in color and a number of tube worms are present. Shell is hard and ventrally may be dark-cream colored and covered with discolored scratches. Chela does not bend or break when moderate thumb pressure is applied. Iridescence on chelae is reduced in intensity. This category generally applies to animals that have molted up to two years prior to capture.

Old/Hard (3) Carapace is dull brown in color and an assortment of calcareous tube worms and barnacles are present. The shell, although still hard, may have a slight "leathery" feel. Ventrally, the shell is brownish in color and many dark scratches evident. Iridescence on chelae is faint or absent. This category applies to animals that have not molted for at least two years.

Bottom temperatures from depths ≥170 m were obtained from an oceanographic station (Station 27) near the Avalon Peninsula fishing grounds (Fig. 1). There is no oceanographic station in Bonavista Bay, but bottom temperatures were obtained during eight research cruises by using expendable bathythermographs, or reversing thermometers.

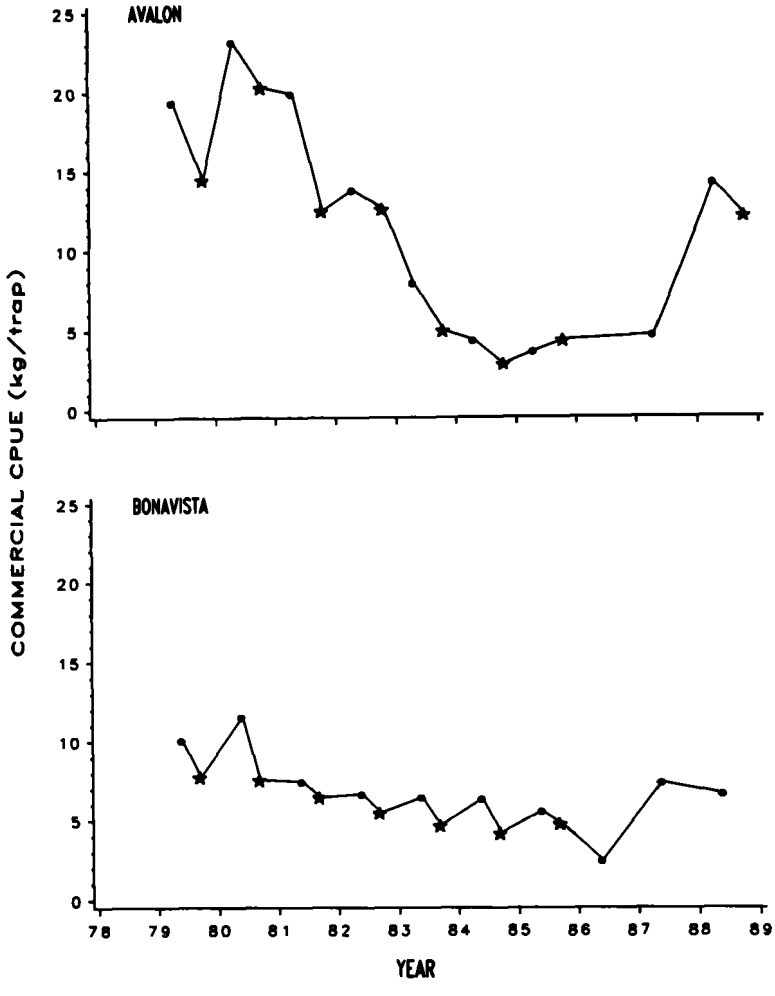

Figure 3

Commercial CPUE's for the Avalon Peninsula and Bonavista snow crab, *Chionoecetes opilio*, fisheries, 1979–88. Solid circles represent spring catch rates; stars represent fall catch rates.

CPUE's were derived for research fishing by multiplying the number of commercial crab caught per trap haul by a conversion factor of 0.45 kg/crab (Taylor, unpubl. data). Fishermen's logbook catch data were checked against processors' purchase slips. CPUE from logbook data was corrected for the percentage of sublegal crab in their catch as determined from sampling at processing plants conducted simultaneously with the research cruises. Total catch reported by log/purchase slips was then multiplied by the percentage of legal-sized animals and divided by the reported effort for the same time period to obtain a CPUE value comparable to that derived from a coincident research cruise.

Results

Logbook data

Landings and effort data from commercial logbooks are summarized in Figure 2. The drop in effort and landings for the Avalon Peninsula in 1980 is the result of a labor dispute and probably does not reflect abundance. Fishery CPUE in both the Avalon and Bonavista Bay areas was at its highest levels during the spring 1980 at 23.2 kg/trap haul and 11.6 kg/trap haul, respectively (Fig. 3). However, off the Avalon Peninsula, catch rates dropped to 19.9 kg/trap haul during the 1981 spring fishery as landings peaked at approximately 8500 t. CPUE declined to 13.8 kg/trap haul in 1982 despite logbook reports that new commercial fishing grounds were being exploited in the offshore areas (>100 km from land). This decline continued, reaching 3.7 kg/trap haul in the spring fishery of 1985 (Fig. 3), a drop of 84% from 1980 levels. This decline in CPUE was accompanied by a dramatic reduction in effort falling from 480,000 trap hauls in 1981 to 17,000 in 1985 (Fig. 2).

In comparison, the commercial spring fishery in Bonavista Bay, although overexploited (Taylor and O'Keefe[4]), has maintained a comparatively stable level of landings and CPUE since 1981 (905–1805 t and 4.1–to 8.2 kg/trap haul, respectively, despite an overall increase in effort from 1980 levels [Fig. 2]). Unlike the Avalon Peninsula fishery, spring catch rates in this area consistently reflect growth and recruitment into the commercial biomass as newly molted individuals recover to commercial acceptability over winter.

Research cruise CPUE and shell condition data

Logbook-derived commercial CPUEs and research cruise CPUE data with calculated confidence intervals are represented in Figures 3 and 4, respectively. Confidence intervals for most offshore Avalon research cruise CPUE data are fairly tight, with the exception of those data from a February 1986 cruise.

[4] Taylor, D. M., and P. G. O'Keefe. 1987. Analysis of the snow crab (*Chionoecetes opilio*) fishery in Newfoundland for 1986. Can. Atl. Fish. Sci. Advis. Comm. CAFSAC Res. Doc. 87/57, Dartmouth, Nova Scotia, 26 p.

These CPUE values were derived from only four fishing sets that were placed on the commercial fishing grounds opportunistically.

On the commercial fishing grounds off the Avalon Peninsula, CPUE's derived from research cruises were nearly identical to those of commercial enterprises at approximately 19.5 kg/trap haul in 1979 (spring). However, CPUEs diverged over the years primarily because commercial vessels had a greater fishing range than the research vessels. Nevertheless, the sharp drop in CPUE between 1982 and 1983 was reflected in both the commercial and research cruise data. In the commercial fishery, CPUE dropped from 13.8 kg/trap haul in the spring of 1982 to 8.0 kg/trap haul in the spring of 1983 (Fig. 3). This decline in crab abundance was mirrored in research cruise data, which indicate a decline from 9.3 kg/trap haul to 2.9 kg/trap haul over the same period (Fig. 4).

Research cruise data for this period in Bonavista Bay are not available. Logbook data, however, indicate that CPUE dropped by only 0.2 kg/trap haul (Fig. 4).

Data on shell conditions of legal-sized and prerecruit crabs from research cruises conducted off the Avalon Peninsula demonstrate that the drop in CPUE coincided with a decline in the proportion of new-shelled crabs from 52.4% to 18.6% (Fig. 5). In Bonavista Bay, the percentage of new-shelled animals dropped to 68.4% in the fall of 1983 from 97.7% in the spring of 1982. However, the proportion of new-shelled animals quickly rebounded to 97% in 1984 as opposed to 40.6% off the Avalon Peninsula during the same year.

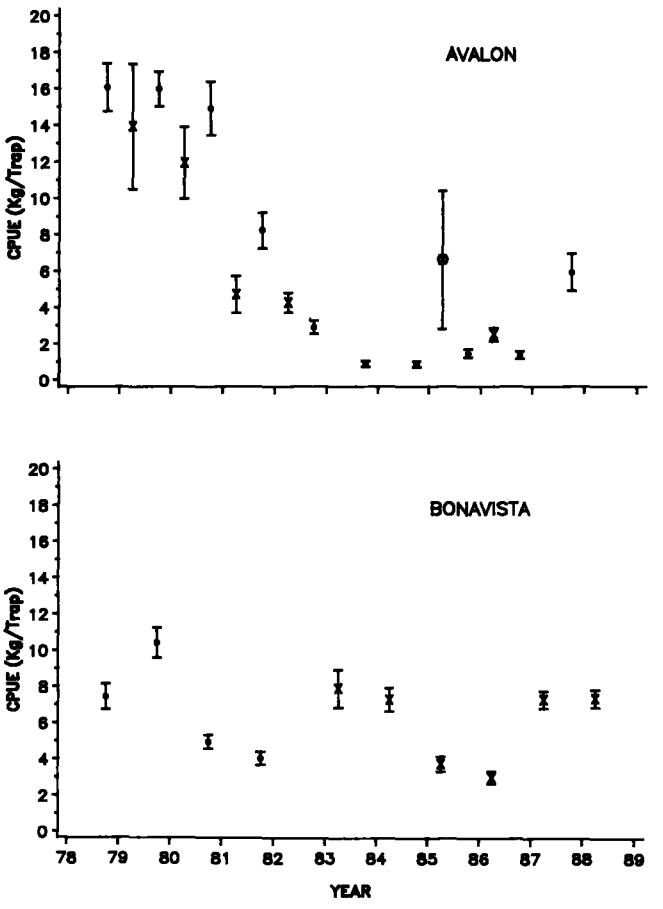

Figure 4

Research cruise CPUE's with calculated confidence intervals for the Avalon Peninsula and Bonavista Bay, 1979–88. Solid circles represent spring cruises and X's represent fall cruises. A circled 'X' is used to highlight data from the February 1986 cruise during which only 4 stations were fished in a nonrandom manner.

Temperature data

From the spring of 1978 through the first half of 1982, mean bottom temperature ranged from –0.3° C to –0.8°C off the Avalon Peninsula (Fig. 5). During the second half of 1982, the beginning of a trend towards colder bottom temperatures was evident. Bottom temperatures during this period dropped as low as –1.6° C and rarely rose above –1.0°C the entire period of mid 1982 to 1986. Two brief periods of warming occurred in both 1983 and 1984 but these periods were short-lived and weak. In 1986 a general warming trend began with an increase from the 1985 low of –1.6°C to around –1.1°C, a trend that has continued to the present.

The drop in temperature and the decrease in the proportion of new-shelled crabs appeared to coincide with bottom temperatures declining during April–May of 1982 whereas the percentage of new-shelled crabs dropped from 52.4% in April to 17.0% in September. Figure 5 illustrates that between 1982 and 1986 there were two brief periods (1983 and 1984) when mean bottom temperature at Station 27 increased slightly and coincidental increases in the proportion of new-shelled animals followed in 1984 and 1985. This delay between increase in water temperatures and appearance of new-shelled crabs is consistent with our current understanding of snow crab molting mechanisms (Moriyasu[5]).

The warming trend in July 1984 was short-lived (Fig. 5). During 1985 water temperatures dropped to the lowest level of all the years examined. Shell

[5] Moriyasu, M. Dept. Fisheries And Oceans, Gulf Fisheries Centre, Box 5030, Moncton, N.B. E1C 9B6. Personal commun. April, 1987.

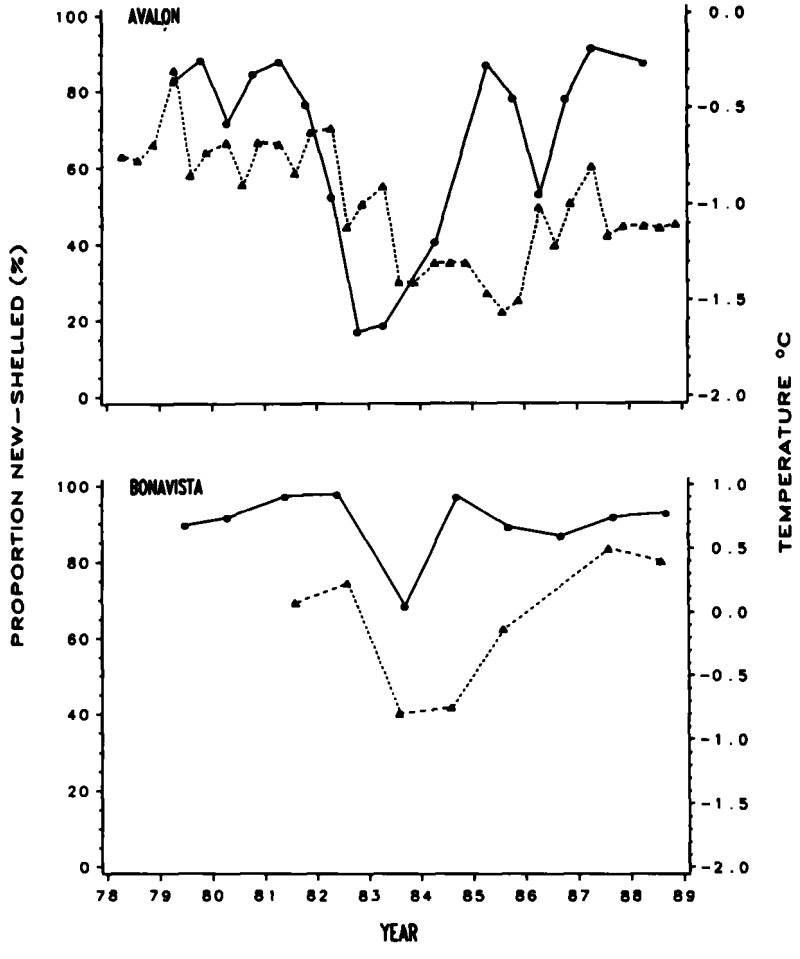

Figure 5

Changes in the percentages of new-shelled Avalon Peninsula and Bonavista Bay *Chionoecetes opilio* males ≥ 70 mm CW in relation to changes in bottom water temperatures on snow crab commercial fishing grounds, 1979–88. Solid circles connected by solid lines represent the proportion of new-shelled crabs and the triangles connected by a broken line represent bottom water temperature.

condition sampling in February 1986 indicated no molting activity during the summer and fall of 1985 (Fig. 5).

A further indication that the impact of these increases in new-shelled animals was minimal is illustrated by continuing low CPUE's (Figs. 3 and 4). Large proportions of new-shelled animals and higher CPUEs were not observed until the warming trend of 1986 was firmly established. While the decline in temperature between 1982 and 1983 is mirrored in data collected during Bonavista Bay research cruises (Fig. 5), the lowest temperatures encountered in Bonavista Bay are roughly equivalent to normal temperatures at Station 27 off Avalon Peninsula.

Although there was a significant decline in the proportion of new-shelled crab in 1983 after the water temperature declined (68.4% vs. 97.7%) in the spring of 1982 this value quickly rebounds in 1984 to 97.0% despite only a marginal warming of the water (Fig. 5).

Discussion

The tight confidence intervals for the Avalon Peninsula research cruise CPUE's (Fig. 4) for 1982–1987 (except February 1986) are indicative of just how severe, widespread, and enduring the resource depletion was in this area. Each research survey fished stations randomly selected and stratified by depth and covered virtually all the approximately 3600 sq. km. of commercial snow crab fishing grounds (Taylor et al.[6]). Had a sustained recovery been made by the crab population in any section of the commercial fishing grounds, it would have almost certainly been detected, either by our research cruises or by commercial crab fishermen.

Little is known about environmental factors that affect snow crab molting physiology. Low water temperatures may inhibit molting in crabs (Hiatt, 1948; Adelung, 1971; Leffler, 1972; Warner, 1977) and other decapods (Travis, 1954; Aiken, 1980; Ennis, 1983).

Foyle (1987) determined that snow crab from Cape Breton Island are able to maintain normal physiological functions at temperatures much higher than their normal temperature range. At high temperatures however and at temperatures below 1°C, reproductive growth and net energy consumption become slightly negative. Snow crab on the northeast coast of Newfoundland live at much lower water temperatures (<-0.75°C) than do those off the Cape Breton Island and a drop in temperature may result in such a "deficit" in their energy budget that molting physiology is impaired.

[6] Taylor, D. M., W. R. Squires, and P. G. O'Keefe. 1983. An alternate methodology for estimating snow crab (*Chionoecetes opilio*) populations in commercially fished areas. Can. Atl. Fish. Sci. Advis. Comm. CAFSAC Res. Doc. 83/1, Dartmouth, Nova Scotia, 10 p.

Aiken (1980) demonstrated that molting is inhibited in American lobsters, *Homarus americanus*, at 5° C if active premolt is not achieved before water temperature drops to that level. A similar physiological response to declining temperature may have contributed to the apparent reduction in molting in the snow crab population off the Avalon Peninsula after temperature dropped in 1982.

Molting in Newfoundland snow crab in this area generally occurs during May–August. The sharp decline in abundance of new-shelled crab in September indicated that many animals that would normally molt during this period apparently failed to do so, possibly as a result of extremely cold water temperatures.

Both Bonavista Bay and the offshore Avalon are affected by the Labrador Current. In 1982 the current became wider and deeper than in previous years causing a cooling effect throughout the water column (Akenhead[7]). Whereas this phenomenon affected the entire east coast of Newfoundland, it was most severe near the Avalon Peninsula primarily because of its comparative shallowness (174–200 m). Bonavista Bay is 220–486 m deep on the crab grounds and its depth may reduce the cooling effect of the Labrador Current (Akenhead[8]). This may explain why snow crab molting activity here was not as adversely affected as it was on the Avalon crab fishing grounds (Fig. 5).

The lack of recruitment into the fishery, between 1982 and 1986, meant that the snow crab resource off the Avalon Peninsula had been in effect "mined" rather than harvested as a renewable resource. The impact of the decline in snow crab abundance was dramatic. This marked decline in landings, from the Avalon Peninsula area, resulted in a substantial drop in employment and earnings from the snow crab fishery (Collins[9]).

Evidence of a link between temperature and molting is circumstantial. However, the drop in water temperature followed by a rapid decline in molting activity (Fig. 5), and subsequently CPUE (Fig. 4), makes a compelling argument that the yearly proportion of snow crab molting in an area is largely dependent on environmental conditions in the particular case where temperatures are very low and variable. The argument is supported by the observation that twice between 1984 and 1988 water temperatures rose and fell, affecting subsequent changes in the proportions of crabs molting off the Avalon Peninsula (Fig. 5). If molting of pre-recruit snow crabs and consequent recruitment into the fishery are affected by changes in water temperature, the impact of these changes should be included in resource management programs. The existing policy of allowing yearly exploitation rates of 50–60% should be re-examined. As the effects of these environmental changes may be long term, recommended exploitation rates could be reduced to prolong a fishery in which recruitment has been interrupted. Assessments of the fishery off the Avalon Peninsula (Taylor and O'Keefe[4]) indicate that exploitation rates were <65% between 1979 and 1981. However, owing to the failure of undersized males to molt into the fishery beginning in 1982, each successive year's standing stock was reduced until fishing was no longer economically viable. In contrast, although exploitation rates in Bonavista Bay consistently exceeded 75% (Taylor and O'Keefe[10], 1983[11], 1984b[12], and 1987[4]), molting within the population continued to provide sufficient recruitment for a viable fishery even though catch rates declined. With the exception of 1983 when the incidence of new-shelled animals (shell condition 1 and 2) in research cruise catches fell to 68% (Fig. 5), new-shelled animals composed in excess of 85% of the catch of legal-sized and immediate pre-recruits. This high level of molting appears to have prevented the precipitous decline in catches experienced in the offshore Avalon Peninsula area.

To prevent future declines of such proportions it may be advisable to monitor temperature, catch rates, and crab shell condition more closely on a seasonal basis. Efforts should also be made to determine thermal requirements for molting in snow crab. The implications for resource management strategy are simply that, regardless of exploitation levels, changes in temperature likely affect molting and hence recruitment to the standing stock to such an extent that assumptions regarding long-term sustainability of annual landings are not justified.

[7] Akenhead, S. A. 1986. The decline of summer subsurface temperatures on the Grand Bank, at 47°N, 1978–1985. NAFO SCR Doc. 86/25, 8 p.

[8] Akenhead, S. A. Institute of Ocean Sciences, Box 6000, Saanick Rd. Sydney, B.C. V8l 4B2. Personal commun., April 1987.

[9] Collins, J. F. Chief, Economic Analysis Division, Program Coordination & Economics Branch, Northwest Atlantic Fisheries Centre, P.O. Box 5667, St. John's, Newfoundland A1C 5X1. Personal commun. September 1993.

[10] Taylor, D. M., and P. G. O'Keefe. 1981. Assessment of snow crab (*Chionoecetes opilio*) stocks in Newfoundland, 1979. Can. Atl. Fish. Sci. Advis. Comm. CAFSAC Res. Doc. 81/57, Dartmouth, Nova Scotia, 34 p.

[11] Taylor, D. M., and P. G. O'Keefe. 1983. Assessment of snow crab (*Chionoecetes opilio*) stocks, in Newfoundland in 1980. Can. Atl. Fish. Sci. Advis. Comm. CAFSAC Res. Doc. 83/3, Dartmouth, Nova Scotia, 40 p.

[12] Taylor, D. M., and P. G. O'Keefe. 1984b. Assessment of Newfoundland snow crab (*Chionoecetes opilio*) stocks in Newfoundland for 1982. Can. Atl. Fish. Sci. Advis. Comm. CAFSAC Res. Doc. 84/3, Dartmouth, Nova Scotia, 30 p.

Acknowledgments

The authors are indebted to the crews of the C. S. S. *Shamook* and *Marinus* who provided able support during the research cruises. G. P. Ennis, J. Hoenig, R. Knoechel, D. G. Parsons, and P. Schwinghamer provided helpful comments on the manuscript. P. Collins, H. Mullett and G. King prepared the figures while M. Hynes and J. Lannon typed the manuscript.

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