**Introduction:**

The snow crab (*Chionoecetes opilio*) fishery is one of the primary economic drivers in Canada’s Atlantic provinces with an export value of $1.87 billion in 2021 [2]. These crab are a common cold-water species found in northern regions from Greenland, northern Europe, Russia, Japan, the Bering Sea, and eastern Canada. Canadian snow crab populations are found off the coasts of Nova Scotia and Newfoundland and Labrador, as well as the northern and southern portions of the Gulf of Saint Lawrence.

Snow crab grow to commercial size in 8-10 years through a process called molting, whereby the old crab shell is shed, then replaced by a new, larger shell, which is initially soft, but subsequently hardens over a period of 8 to 10 months. Soft-shelled crab are vulnerable to predation by other species, as well as other snow crab, which are known to cannibalize each other. Snow crab do not continue to molt throughout their lifespan, but rather undergo a final, terminal molt after which they attain full sexual maturity (Conan and Comeau 1986; Comeau and Conan 1992). Male crab generally reach sexual maturity at about the minimum legal size of crab, which corresponds to a carapace width of 95 millimeters, but can grow to as large as 140 millimeters. Female snow crab are much smaller and are not fished commercially.

Due to the terminal molt, commercial-sized crab will naturally age over time, with the carapace becoming progressively fouled with organisms, accumulating wear, scars and often losing legs over time. Because of these growth and ageing processes, there are different types of commercial-sized crab: soft-shelled crab, hard-shelled crab and old or ageing crab, with each of these categories having different importance in terms of management of the fishery and market implications. Soft-shelled crab represents future recruits to the fishery, hard-shelled crab are those that are targeted by the fishery, and old-shelled crab are less desirable from a marketing stand-point.

Thus a rating system was developed to classify the relative condition of the snow crab carapace. This scale is based on the subjective evaluation of external characters, ranging from 1 (new-shelled) to 5 (old-shelled crab). This scale is based on a collection of subjective criteria, ranging from the hardness of the shell, its color, the level of fouling organisms and visible wear on the carapace (Table 1). This scale is in common use in stock assessments, and is commonly used to identify incoming recruitment to the fishery or the quantity of crab left over after the fishery.

**Soft-shelled crab protocol:**

Another important management application was the protection of soft-shelled crab during fishing activities. Soft-shelled crab in fishery catches are discarded (i.e. returned to sea) because they have a low meat yield. This is because it takes time for the crab’s muscle mass to expand to the dimensions of the new shell. However, handling by fishermen and the shock of being hauled from dark, cold, deep waters and dumped onto the fishing vessel’s deck, only to be thrown back into the ocean is often accompanied by mortality for these crab. To remedy this, a protocol was put in place by the Department of Fisheries & Oceans (DFO) in order to minimize the capture of soft-shells during the fishing season. Under this protocol, local area closures are triggered when incidence of soft-shells in catches are deemed too high. Such protection of soft-shelled crab is a good idea, in that these crab will become commercially viable the following year (i.e. the meat yield increases). The shell condition scale is thus used by on-board fishery observers to identify soft-shelled crab.

However, application of the shell condition scale is not without issues. Because the scale is based on subjective criteria, interpretations may vary from one observer to another. Such inconsistencies may lead to biases in the estimates of different crab groups, or weaken the management protections for soft-shelled crab, for example. In this paper, we develop a AI methods which can identify the shell condition of snow crab from a set of photos with good accuracy. Different methods were tested and compared.

An AI shell condition identifier will automate the subjective and improve the consistency of its application.

The correspondence between the shell condition identification and different measured material properties of the carapace will also be discussed.

**Of course, the ideal case would be to have age determinations on the carapace shells, which would allow for characterizing new fishery recruits and modeling annual dynamics between the age groups.**

**A lesser goal would be to have a measure which neatly clusters new-shelled (i.e. have moulted less than a year ago) and old-shelled crab. Some measures, like measuring meat yield, do exist, but they are laborious (require lab analysis) and destructive.**

**Indirect measures of meat yield, such as ultrasonic measures, might also be possible.**

In terms of management and assessing the stock and its dynamics,

*Caveats:*

*The methods presented is this document do not:*

* *Provide a means of assessing the validity/consistency of the shell condition scale itself, but only in replicating the particular assessments made by trained DFO technicians during science surveys.*

This raises multidimensional challenges, including the need to characterize

exoskeletal hardness, color and other physical properties to determine maturity and

quality. In addition, natural variability between individuals and environmental conditions

calls for accurate, non-invasive characterization methods. In this context,

combining data from NIR spectroscopy with crab imagery presents a promising

integrated approach to addressing this challenge.

The classification of soft-shell and hard-shell snow crabs is an essential task in

the seafood industry, as it has a direct impact on product quality and market value.

Several techniques have been studied to meet this challenge, drawing on advances in

imaging, spectroscopy and sensor technologies.

An exhaustive review of the literature revealed little published work on assessing

the shell condition of snow crabs or crustaceans in general.

Durometers, used inindustry to measure the hardness of elastomeric materials (rubber, plastic, etc.), have

been employed to assess the hardness of crab shells [3].

However, standard durometers are not suitable for measuring the hardness of snow crab shells, as their pointed penetrator is too sharp and pierces the shells [4].

**Ultrasound :**

*In the aquaculture context*, Sutherland et al [5] used ultrasound imaging to visualize the growth of the new

branchiostegal plate just below the exoskeleton of tropical rock lobster. The authors

of [6] studied the characterization of tropical spiny lobsters (*Panulirus ornatus*) in

order to prevent cannibalism by detecting pre-molting individuals*, developing a*

*low-cost spectral camera to this end.*

In [7], the use of non-destructive testing (NDT) ultrasound is explored to detect

pre-molt in juvenile tropical lobsters (Panulirus ornatus), which exhibit high levels of

cannibalism in culture. Implementing a pre-molt sensor could help reduce losses from

cannibalism, as molting lobsters are the primary victims. Although internal changes

are difficult to observe externally, the study demonstrates that a 13 mm, 7 MHz

transducer generates a distinctive signal in inter-molting lobsters, which is absent in

pre-molting individuals.

Mehr¨ubeoglu et al. conducted a comparative study using three imaging modalities,

including hyperspectral imaging, thermal imaging and digital photography, to assess

oyster shell thickness and strength. Although the study focused on oysters, the principles

can be extended to snow crabs. Hyperspectral imaging, in particular, showed

promising correlations with shell strength, indicating its potential for assessing the

hardness of crab shells [8].

Microwave sensor technology offers another opportunity for non-destructive evaluation

in food analysis [9]. Although mainly applied in the laboratory, its potential for

on-line measurement in the food industry underlines its relevance for assessing crab

shell characteristics quickly and hygienically.

Near infrared (NIR) spectroscopy has also become a powerful tool for food authentication

and quality assessment [10, 11]. By analyzing the NIR spectra of fish skin

and meat, researchers have been able to distinguish high-quality species from inferior

ones. This approach could be adapted to distinguish soft-shelled from hard-shelled

snow crabs on the basis of spectral differences in shell composition.

Furthermore, the application of NIR spectroscopy to assess the nutritional status

of lobster demonstrates its potential for the analysis of crustaceans [12]. By correlating

NIR spectra with nutritional indices, the researchers were able to assess lobster

condition non-invasively. Similar methodologies could be applied to assess the quality

of snow crab shells.

In addition, Guan et al. proposed a new method combining colorimetric sensor

arrays with visible near-infrared spectroscopy for oyster freshness identification.

Although focused on oysters, this approach demonstrates the potential of spectroscopic

techniques coupled with image processing to assess shell quality in crustaceans [13].

In summary, the combination of imaging, spectroscopy and sensor technologies

offers promising possibilities for the classification of soft-shell and hard-shell snow

crabs. By taking advantage of these techniques, researchers and industry professionals

can improve quality control measures and guarantee the integrity of snow crab

products on the market.

NIR spectroscopic analysis can reveal molecular signatures and structural features

of exoskeletons [14]. At the same time, images of the crabs enable visual and

morphological assessment of the changes associated with molting.

The primary objective of this study is to explore and develop an innovative

method for characterizing snow crab exoskeletons, aimed at improving the sustainable

management of populations and guaranteeing the quality of seafood products for

future generations.

To achieve this, it proposes an integrated approach that combines

near-infrared (NIR) spectroscopy and image analysis techniques to develop a robust

classification system for identifying snow crab shell condition.

However, this work is not without its constraints, particularly when it comes to

collecting data.

Collection will take place in conditions where fishermen handle crabs

and use measuring devices such as the NIR spectrometer and photo-taking.

Consequently, one of the major constraints is identifying the best device in terms of ease

of use and speed. It is essential to select non-destructive testing NDT instruments

and measurement methods that minimize stress and disturbance to the crabs, while

guaranteeing the reliability and quality of the data collected [7]. This consideration is

crucial to ensure the validity of the results obtained, and to guarantee the well-being

of the crabs and the sustainability of data collection practices in the field.

**Goals of the study:**

* Methods which are robust, speedy and easy to use.
* Rough field conditions (i.e. rain, wind, salt-water, dirty)
* non-destructive testing to minimize stress and disturbance to the crabs, guarantee the well-being of the crabs
* guaranteeing the reliability and quality of the data collected.
* Validate new-shell versus old-shelled crab groups.
* Improve the consistency of shell condition identifications between different observers.

**Applications of shell condition identification:**

* Monitor market quality (meat yield, visual appeal) of commercially exploited crab (i.e. mature legal-sized crabs).
* Monitor the occurrence of new-shelled crab during the fishery, which triggers local area closures if proportions are too high.
* Relative measure of carapace age (i.e. time elapsed since last moult).
* Identify new recruits to fishery and crab which skip a moult.

Differences between the aquaculture and fishery context:

* Product quality is ensured by triage on board vessels.

2 Materials and Methods

2.1 Near-Infrared Spectroscopy

NIR spectroscopy, which operates in the electromagnetic spectrum from 780 to 2500

nm, offers a powerful tool for identifying the different stages of shell development in

snow crab.

NIR spectra encompass signals from many major structures and functional

groups present in organic compounds found in foods.

In the context of assessing snow crabs for stages of shell development, the broad NIR bands arise primarily from overlapping absorption features associated with vibrational C-H and O-H chemical bonds.

These bonds are mainly related to water and storage reserves, the dominant macroconstituents

in crab tissues.

The intensity of the bands involved weakens towards shorter wavelengths.

Lower intensities in the near-infrared region mean that solid samples do not need to be diluted, and that non-linearity effects due to strong absorption are less likely.

The interaction of near-infrared radiation with solid particles gives rise to

refraction, transmittance, absorption and scattering effects, as shown in Figure 1 [15].

The use of NIR spectroscopy offers several advantages for the identification of shell

condition in snow crab.

It facilitates rapid acquisition of spectra, requires minimal

sample preparation and generates no chemical waste.

In addition, NIR spectrometers have the ability to characterize a wide range of samples in different forms, including solids, liquids and mashes. However, to accurately predict crab shell condition

using NIR spectra, an initial calibration step is essential, albeit time-consuming. This

calibration process involves establishing predictive models through multivariate statistical

and mathematical analyses of the data using a set of representative samples that

encompass the expected variability. NIR spectra and corresponding reference data for

shell development stages are essential for developing robust predictive models. The

Tellspec tool was used as a sensor to collect NIR spectra in absorption mode, covering

a wavelength range from 900 to 1700 nm, with a 5 mm x 9 mm window and a

uniformly distributed spectral resolution of 3 nm [16].

The Tellspec spectrometer is presented as a high-performance, portable device

capable of assessing food composition at a fraction of the cost of traditional NIR

systems used in the laboratory.

2.2 Collection and Identification

Specimens of *Chionoecetes opilio* were obtained by trap fishing. The first data collection

was conducted between September 4th to the 11th 2023, off the coast of

Cheticamp, Cape Breton. with the capture of around 70 male snow crabs, followed by

a second session in May 2024 gathered by Fisheries and Oceans Canada (DFO) Science

staff from the 2024 Area 12 fishery in the southern Gulf of Saint Lawrence and

a local crab processing plant, during which a further 60 male crabs were caught.

Each specimen was meticulously measured and manipulated using a variety of

instruments on board, including a spectrometer, durometer and colorimeter, to obtain

precise details of their carapace characteristics.

Particular attention was paid to two specific areas: the merus and chela of crabs, as these regions are indicative of the overall condition of the shell.

Alongside the physical measurements, comprehensive visual documentation was

carried out using imagery.

Ventral and dorsal images of each snow crab were taken, providing detailed visual representations of the specimens’ bellies and backs.

These images were to form the basis for the development of computer vision models for

classification purposes.

During the data collection phase, the shell condition of each crab was assessed

and graded on a five-level scale, from 1 (softest) to 5 (hardest).

The majority of crabs caught during the first collection were manually graded between levels 3 and 5,

indicating moderate to high shell hardness.

Only one specimen was graded at level 2, signifying a softer carapace than the other crabs. It is also notable that no specimens were classified at level 1, highlighting the prevalence of moderate to high shell hardness at the end of the fishing season.

In contrast, during the second collection, carried out at the start of the fishing

season, a greater number of crabs were classified at levels 1 and 2, reflecting softer

carapaces. Table 1 presents the novel finger pressure subjective scale used in the data

collection process.

Conan, G. Y. & M. Comeau, 1986. Functional maturity of male snow crab (*Chionoecetes opilio*). Canadian J. Fish. Aquat. Sci., 43: 1710-1719.

Table X : Shell condition (SC) stages used to rate the external appearance and condition of snow crab in the southern Gulf of Saint Lawrence (modified from Conan & Comeau, 1986).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Condition** | **Hardness** | **Appearance** | **Dorsal color** | **Ventral color** | **Carapace age** |
| 1 (New soft) | Soft | Clean | Light brown | White & iridescent | < 3 months |
| 2 (New hard) | Harder | Clean | Light brown | White & iridescent | 3-12 months |
| 3 (Intermediate) | Hard | Less clean | Brown | Beige-yellow | 1-2 years |
| 4 (Old) | Hard | Dirty | Dark brown | Yellow-brown | 2-4 years |
| 5 (Very old) | Decalcifying | Very dirty | Dark brown | brown | 4+ years |

The main data points collected during the data collection process are presented in

2.3 Data processing and augmentation

The data were pre-processed to facilitate the integration of NIR data with other data

types in a unified CSV file. Notably, in this study, NIR absorbance data were used

rather than reflectance data. In the field of NIR data classification, the integration of

principal component analysis (PCA) with a multilayer perceptron (MLP) is a powerful

combination of algorithms that has proven its effectiveness. PCA is a valuable

pre-processing step, effectively reducing the dimensionality of NIR spectral data while

retaining the most relevant information. By transforming the original spectral features

into a lower-dimensional space defined by principal components, PCA simplifies

the subsequent classification task and improves computational efficiency. Next, MLP,

a type of artificial neural network known for its ability to learn complex patterns and

relationships within data, is used for classification [17]. The MLP takes advantage

of the reduced-dimensional feature space generated by the PCA to efficiently discern

subtle spectral variations indicative of different crab shell states. Through iterative

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Table 2: Description of the fields in the dataset.

Field Description

crab.number A unique identification number was assigned to each captured crab to facilitate individual

tracking and data management throughout the study.

sex The sex of each crab was recorded, distinguishing between male and female specimens,

allowing a better understanding of potential sex-related differences in shell condition.

width, height Physical measurements, including carapace width and claw height (Chela), were

meticulously recorded to quantify the size and morphology of each crab.

durometer Durometric values, representing carapace hardness, were measured using a durometer

device, providing quantitative data on carapace rigidity.

hemolymph Hemolymph samples were taken from each crab to assess physiological parameters

and potential indicators of stress or health status.

colorimeter Colorimetric analysis was carried out to quantify the coloration of crab shells, providing

further information on shell condition and potential variations in pigmentation.

NIR scan Near infrared (NIR) spectroscopy data were collected using the Tellspec Enterprise

scanner to capture spectral information relating to shell composition and structural

properties, providing a non-destructive testing (NDT) method for assessing shell condition.

shell.condition In addition, the shell condition of each crab was manually identified and classified

into specific classes (1 to 5) on the basis of visual inspection, providing a qualitative

assessment of shell hardness.

training and optimization, the MLP model learns to accurately classify NIR spectra,

enabling robust and reliable identification of snow crab states. This synergistic

approach capitalizes on the strengths of PCA and MLP, resulting in a powerful framework

for classifying NIR data in the context of assessing crab shell condition [18]. In

addition to NIR data, the pre-processing of crab images is essential to enable their use

in crab shell condition classification. The initial step is to detect the region of interest

(ROI) in each image, which will be used to develop the classification model. Given

the potentially large volume of image data, it is imperative to automate this detection

process. In this context, we have deployed the new YOLO11 algorithm for the

accurate detection of snow crab bellies from raw images. To optimize the performance

of this algorithm, we built up an extended database, incorporating images of snow

crabs with various shell conditions. This database, rich in diversity, comprises a total

of 4071 images, enabling us to guarantee greater robustness and accuracy in detection.

Automating the detection process not only improves efficiency, but also ensures

consistency and reproducibility across a diverse range of crab images. We focused our

study on the ventral images of snow crabs in order to exploit the color variations of

this zone during the life cycle of these crabs. An increase in ventral images was necessary

to enrich our database and diversify the samples for each shell condition. Table

3 shows the distribution of the number of crabs captured in each carapace condition

and the corresponding number of ventral images after this augmentation.

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Table 3: Distribution of crabs and ventral images of each condition.

Condition 1 2 3 4 5

Number of crabs 21 7 63 33 13

Number of images 210 51 194 84 39

2.4 Color variability of snow crabs

Snow crabs vary in color from one individual to another. When a crab has just molted,

its new shell is light brown and shiny on top, with no moss or barnacles, and creamy

white underneath, giving it the name “white crab”. This shell is still soft, making the

claws fragile and liable to break. Over time, the shell ages, hardens and takes on a

dark brown hue, often covered with moss, giving it a “dirty” appearance. The white

belly then turns yellowish [19, 20].

(a) (b)

(c) (d)

Fig. 4: Color variation in snow crab shells: (a) dorsal view of a hard shell, (b) ventral

view of a hard shell, (c) dorsal view of a soft shell, (d) ventral view of a soft shell.

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2.5 HSV histogram analysis

The feature extraction process used in this study for crab images is based on the HSV

(hue, saturation, value) format. First, the images are converted from RGB to HSV format.

This conversion is advantageous because the HSV representation separates the

color information (hue) from the intensity and saturation components (saturation and

value), which can provide a more intuitive and perceptually relevant color representation

than the RGB format. In the HSV system, the hue component represents the

dominant wavelength of the color, saturation indicates the purity or intensity of the

color, and value corresponds to brightness or clarity. By separating these components,

HSV facilitates the interpretation and manipulation of color information, making it

well suited to tasks such as color-based image analysis and processing.

The conversion of RGB to HSV is presented as follows [21]. First, the maximum

intensity of RGB is determined as Imax = max(R, G,B), the minimum intensity of

RGB is determined as Imin = min(R, G,B), and the intensity range is calculated from

Imax and Imin as Idiff = Imax − Imin. Next, H, S, and V are calculated as

H =





0 if Imax = Imin

(60◦ × G−B

Idiff

+ 0◦) mod 360◦ if Imax = R

(60◦ × B−R

Idiff

+ 120◦) if Imax = G

(60◦ × R−G

Idiff

+ 240◦) if Imax = B

S =

(

0 if Imax = 0

Idiff

Imax

else

V = Imax

(1)

Furthermore, the pixel range of HSV and RGB are as summarized in Table 4

Table 4: Color space of HSV and RGB.

H S V R G B

Min 0 0 0 0 0 0

Max 360 100 100 255 255 255

Once images are in HSV format, the histogram of each channel (hue, saturation,

value) is calculated. The histogram represents the distribution of pixel intensities

in each channel, giving an idea of the image’s color composition. These histograms

serve as feature vectors, capturing the color characteristics of crab shells, and are

used as inputs for classification algorithms. Using HSV-based feature extraction,

this approach enables classification algorithms to efficiently exploit image color

information, contributing to the accurate classification of crab shell hardness levels.

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(a) (b)

(c) (d)

Fig. 5: Images of ventral hard and soft shells in RGB and HSV formats: (a) RGB

representation of a hard shell crab, (b) HSV representation of a hard shell crab, (c)

RGB representation of a soft shell crab, (d) HSV representation of a soft shell crab.