AFSC PROCESSED REPORT 2021-04

NOAA FISHERIES

Alaska Fisheries Science Center

Inventory, Management Uses, and Recommendations for Fish and Crab Condition Information from the 2021 AFSC Condition Congress

SEPTEMBER 2021

U.S. Department of Commerce | National Oceanic and Atmospheric Administration | National Marine Fisheries Service

AFSC Processed Report

This document should be cited as follows:

Hurst, T. P., C. A. O'Leary, S. K. Rohan, E. C. Siddon, J. T. Thorson, and J. J. Vollenweider. 2021. Inventory, management uses, and recommendations for fish and crab condition information from the 2021 AFSC Condition Congress. AFSC Processed Rep. 2021-04, 39 p. Alaska Fish. Sci. Cent., NOAA, Natl. Mar. Fish. Serv., 7600 Sand Point Way NE, Seattle WA 98115.

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Inventory, Management Uses, and Recommendations for Fish and Crab Condition Information from the 2021 AFSC Condition Congress

T. P. Hurst[1], C. A. O'Leary[2], S. K. Rohan[2], E. C. Siddon[3],

J. T. Thorson[4], and J. J. Vollenweider[5]

[1] Behavioral Ecological Program, Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way NE, Seattle WA 98115

[2] Groundfish Assessment Program, Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way NE, Seattle WA 98115

[3] Ecosystem Monitoring and Assessment, Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way NE, Seattle WA 98115

[4] Habitat and Ecological Process Research Program, Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way NE, Seattle WA 98115

[5] Recruitment Energetics and Coastal Assessment Program, Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way NE, Seattle WA 98115

September 2021

Abstract

Condition indices measure the physiological and energetic status of animals beyond what is explained by organism size. Researchers at NOAA's Alaska Fisheries Science Center organized a Condition Congress in April-May 2021 to inventory, clarify, and recommend future research regarding condition metrics for fishes and crabs. We identify three "classes" of condition metrics (strict measurements, generalized metrics of physiological status, and integrated metrics), and classify twenty ongoing projects within those three classes. We propose five types of uses (i.e., structured and specific decisions that are informed by scientific knowledge) for condition information, including for stock assessment, ecosystem status reports, ecological and socioeconomic profiles, essential fish habitat, and process research, and discuss the policy mandate and current role for condition information in each. We also identify four recommendations: to intercalibrate multiple metrics including easy-to-measure proxies and direct measurements of physiological processes; to use experiments, field-studies, and models to improve the physiological interpretation of condition metrics; to focus research on broad-scale sampling or experimental designs that target population parameters for critical demographic bottlenecks; and to improve the timeliness and standardization of results being communicated among research groups.

We foresee that these recommendations will be useful during project design, proposal writing, and proposal review/evaluation.

Contents

Background

Biological and physiological measures representing the energetic or nutritional status of an organism are categorically referred to as condition metrics or condition indices and are widely applied in fisheries science. These metrics are generally calculated or measured after accounting for variation in organism size, such that the resulting condition metric is interpreted as being independent of the animal size. Morphological condition indices express the relationship between two different aspects of size variation. Historically, the most widely applied (to fishes) morphological index is Fulton's condition factor commonly represented as "K" or "Fulton's K" which expresses the weight of a fish relative to its length using the formula $K = Weight/Length^3$ (Fulton 1904, Nash et al. 2006). There have been numerous refinements to Fulton's K, but they all rely upon describing the mass of an organism relative to body length; for example, Le Cren's condition (Le Cren 1951) accounts for an allometric relationship between length and volume, $K = Weight/Length^b$, where b represents allometric growth.

Another class of condition indicators has focused more directly on measuring the amount of energy in the body or in energy reserves that an animal has accumulated in the form of lipids. Lipids are energy-rich tissues that are used across the animal kingdom as energy deposits, in addition to their other physiological roles in membrane structure, and as precursors for the biosynthesis of steroids and other compounds (Steffens, 1989). Direct energy measurements are based on calorimetric measures and with lipid levels based on proximate composition of the tissues (percent water/lipid/protein/ash). Depending on the size of the organism, measurements can be based on whole organisms or representative tissue samples. This class of indicators can also be represented by measurements of proxies: metrics with recognized relationships to energy density or lipid percentage such as water composition (inversely related to energy/lipid level) and liver mass (directly related to energy/lipid level).

All condition measures are generally assumed to have a functional and direct relationship to survival or fitness, although the direct linkages between condition and survival are not always known. The most basic underlying assumption being that organisms with high condition factors will be better able to tolerate periods of energy stress (e.g., starvation) or will convert stored energy into higher rates of reproductive output. Various attempts have been made to link condition indices to other measures of animal performance such as critical swim speed (Fisher et al. 2005, Litz et al. 2017), predation vulnerability (Booth and Beretta 2004, Hoey and McCormick 2004), or reproductive output (Lambert and Dutil 2000, Kurita et al. 2003, Ballón et al. 2008), but the evidence for such linkages has been mixed.

Energetic condition indices are a subset of a broader suite of indicators of organism state. Other measures or indicators of organism state that are not generally considered condition factors include measures of size, growth rate, maturity, and fecundity. Like condition factors, these state variables are often known or assumed to be related to survival and fitness (e.g., predation mortality is generally assumed to vary inversely with body size). Physiological metrics such as levels of stress or reproductive hormones as well as pathogen/parasite burden can also reflect aspects of the state of an organism and may have hypothetical or demonstrated associations with survival, but they are not traditionally considered condition metrics alongside energetic status indicators.

It is important to note that condition factors (and many state variables) inherently reflect multiple aspects of temporal variation that can affect interpretation. For example, baseline levels of energy reserves vary through ontogeny and have predictable seasonal patterns for many species. Therefore, when applying these measures in data products for applied fishery management, it is essential to isolate the spatial or temporal variation of interest from these intrinsic aspects of variation.

Condition indices and other measures of state are measured at the level of the individual animal, with patterns of variation generally assumed to reflect spatial or temporal variation in the quality of the habitat for the species of interest. As with individuals, this variation is further assumed to translate into spatial or temporal variation in fitness. For example, geographic regions or population cohorts with high condition factors are expected to contribute disproportionately to overall productivity of the population. These arguments are the underpinning for applications of condition measures in essential fish habitat delineation, fishery stock assessments, and ecosystem status reports.

Related to condition indices and measures of state are integrated predictors of organism performance (see Figs. 1-4 for illustration and potential uses). Estimates of growth rate or growth potential based on physiological models are a common example in contemporary fisheries science (Sigler et al. 2017). Two commonly applied frameworks are the energy balance model (commonly referred to as the Wisconsin model, (Kitchell et al. 1977)) and the Dynamic Energy Budget (DEB) model (Kooijman 2009). These models combine descriptions of physiological processes such as size- and temperature-dependent metabolic rates and maximum consumption rates with environmental parameters such as water temperature, prey abundance, and prey energy content. Once the physiological parameters of the model are established, the specificity of the application is dependent upon the spatial and temporal resolution of the dynamic environmental variables and (for growth rate predictions) the realized consumption rates of the consumer (commonly represented as percent of maximum consumption). The models may also include condition factors (such as energy density of the consumer) or other state variables, but most applications are restricted to predictions of organism size and do not predict changes in relative condition in response to environmental factors. As such, they may be considered as providing an independent reflection of productivity to traditional condition factors.

Condition Congress Structure

In January 2021, NOAA's Alaska Fisheries Science Center (AFSC) formed a Steering Committee to host a 2-day workshop called the "2021 AFSC Condition Congress". The Condition Congress was formed with the following objectives:

1. Develop list of metrics being used at AFSC to measure condition-related variables.
2. List representative examples of where condition metrics are being used for fisheries management (including habitat, stock, climate, and ecosystem assessments).
3. Summarize workshop consensus (where it is achieved) regarding which metrics are best for particular process research and/or management applications.
4. Envision future uses for condition metrics, with some suggestions about high-priority topics.

The Congress involved holding a 2-day virtual workshop to solicit input from AFSC staff and affiliates. The first workshop occurred 23 March and involved 16 contributed Lighting talks (summarized in Table 1). The second workshop occurred 13 April and involved a guided discussion of the alternative uses (i.e., structured and specific decisions that are informed by scientific knowledge) of condition metrics.

Working Definition for Condition Metrics

For the Condition Congress, we defined three broad classes of condition metrics:

1. Strict condition: Measures of energetic status for individuals beyond what is captured via body size (e.g., morphometric condition, percent lipid, energy density).
2. Status and performance: Measures of individual performance not specifically measured via #1, and reflecting other aspects of physiological performance of an individual more generally (e.g., growth indicators like RNA:DNA, fecundity, stress hormones, size-at-age).
3. Integrated metrics: integrated measures or predictions of the status or performance of organisms (e.g., bioenergetic estimates of growth rate potential, synthesis of predation rates).

The following includes an inventory and recommendations regarding all three classes (and for each project we identify the class of metric being used).

Inventory of Current Research

Fish condition metrics are a valuable tool utilized by many AFSC staff to produce a variety of products with different end goals. In an effort to inventory current AFSC fish condition research, 16 presentations were given during the Condition Congress as representative examples of where and how condition metrics are being used in research. Specific attributes of each of these presentations are detailed in Table 1. Four additional entries that were not presented are also included. Though not an exhaustive list of all AFSC projects employing condition metrics, this summary is illustrative of who is using these metrics and in what manner.

Fish condition metrics are used by many programs, particularly RACE and RECA, and to a lesser extent in REFM, MESA, and EMA. Direct measurements of condition (Class 1) are the most frequently used metric type, and are almost equally split between analytical chemistry and morphometric measurements. Additionally, several metrics are under development as means to rapidly and inexpensively predict direct measurements of fish condition. Less frequently used are measures of individual performance (Class 2), which are predominantly focused on fish growth. Lastly, integrated metrics (Class 3) such as bioenergetics models are the least commonly used measure of fish condition at AFSC.

Groundfish and pollock make up the majority of species evaluated for body condition, though condition has been evaluated in 79 species of fish, 43 species of zooplankton, 37 species of invertebrates, 6 species of insects, and several species of marine mammals and algae. Among fishes, condition is commonly interpreted in conjunction with prevailing environmental conditions to infer interannual variation in reproductive output and/or survival.

Uses for Condition Information

During the Condition Congress, we identified the following five broad uses for condition information (Stock Assessment, Ecosystem Status Reports, Ecosystem and Socioeconomic Profiles, Habitat Research, and Process Research). We here define uses as instances when condition information is synthesized to inform specific decisions regarding management or scientific operations, or otherwise communicated broadly via scientific journal or other public venue to achieve agreement about a topic that is actively managed. We organize these uses into five categories, and for each category we summarize the policy mandate for these applications as well as how condition metrics could satisfy that mandate.

Stock Assessment

Mandate -- Stock assessments are an iterative and collaborative process for developing SAFE documents, typically involving a stock assessment model but also additional contextual information (e.g., defining stock structure, etc.), and they are reviewed by the North Pacific Fishery Management Council's (NPFMC) Plan Teams and Scientific and Statistical Committee (SSC). The stock assessment model typically uses available time-series information as well as information about biological processes to estimate stock status and allowable biological catch (ABC) given estimated maximum sustainable yield or some established proxy. Stock assessments are the reporting phase of an iterative cycle required by each Fishery Management Plan.

Role for condition -- Stock assessment models (tiers 1-4) typically use a spatially averaged value for morphometric condition as input either implicitly in a pre-specified (and typically time-invariant) weight-at-length function, or as one component in a time-varying empirical weight-at-age matrix. Field measurements of morphometric condition based on length-weight relationships are widely available for groundfishes in bottom trawl surveys. Using morphometric condition in stock assessment informs the conversion from units of numbers/length (demographic variables) to biomass (abundance indices and fishery catch data).

Ecosystem Status Reports (ESRs)

Mandate -- The ESRs compile and summarize current contextual ecosystem information for the NPFMC, the scientific community, and the public to support ecosystem-based fisheries management. Operationally, the ESRs inform the Ecosystem Considerations section of stock-specific risk tables where ecosystem trends that pose increased risk to the stock can support reductions from maximum Acceptable Biological Catches (ABC). ESRs are produced annually for three of Alaska's large marine ecosystems: the eastern Bering Sea (from Aleutian Islands to Bering Strait), Aleutian Islands, and Gulf of Alaska. The ESRs are stipulated in NMFS policy documents and serve as the reporting phase of an iterative Integrated Ecosystem Assessment (IEA) process.

Role for condition -- Groundfish condition indices based on length-weight residuals from the NMFS bottom trawl surveys have been included in the ESRs for many years and are a 'known and expected' part of the ESRs (Rohan and Laman 2020). Several other metrics of physiological performance, such as energy density, are also included. For example, the EBS ESR uses the energy density of age-0 walleye pollock as a leading indicator of age-1 recruitment strength (Siddon et al. 2019). Anecdotally, these indices are an important element of the annual presentation of ESRs to the Plan Teams.

Ecosystem and Socioeconomic Profiles (ESPs)

Mandate -- The ESPs are a relatively new process developed by AFSC (and being replicated at other NMFS science centers) to compile stock-specific ecosystem information structured around conceptual models that allow detailed examination of critical life history bottlenecks. The ESPs serve as a testing ground of ecosystem indicators for stock assessment models in research mode. Indicators that pass through two 'gates' (the first establishes a mechanistic relationship, the second demonstrates improved model fit) may be included in the operational assessment model.

Role for condition -- Groundfish ESPs include morphometric condition indicators based on length-weight relationships from bottom-trawl survey data. The sablefish ESP has condition based on the longline survey for age-4 fish, the longline survey for larger adult females, and the longline fishery for larger adult females. Sablefish previously also used bottom trawl survey data for a morphometric condition indicator. The GOA walleye pollock ESP uses a condition indicator for larval (age-0) walleye pollock from the EcoFOCI survey and adult condition from the trawl fishery. GOA and Bering Sea Pacific cod ESPs have condition indicators for juveniles and adults from the trawl survey and bioenergetics indicators are anticipated for the 2021 Bering Sea Pacific cod ESP.

Habitat Research

Mandate -- The Magnuson-Stevens Fishery Conservation and Management Act and National Standards Guidelines include many mandates for habitat research and management related to condition indices. This includes stipulations the following:

1. Regional fisheries management councils periodically consider updates to areas designated as Essential Fish Habitat (EFH) and Habitat Areas of Particular Concern (HAPC).
2. For stocks below their minimum stock size threshold (MSST), analysts determine whether man-made habitat changes are partially responsible, and if they are, the Council should recommend restoration of habitat and other ameliorative programs.

Role for condition -- The most recent Habitat Research Plan (Sigler et al. 2017) prioritizes funding for projects that identify habitat-specific vital rates (termed "Level-3 EFH information"). During the planned 2022 EFH update, Level-3 EFH information includes projects identifying habitat-specific growth potential for several species (i.e., using a Class-3 condition metric). Analysts propose that this Level-3 information would contextualize the importance of different habitats within designated Essential Fish Habitat layers. This would then allow the Alaska Regional Office to improve their process for EFH consultations. Similarly, improved information linking minimum stock size thresholds to habitat would allow for better interpretation of appropriate management responses in cases where stocks are below their MSST.

Process Research

Mandate -- Process research (research regarding ecological mechanisms conducted primarily via targeted laboratory and field collections, often in conjunction with monitoring and modelling efforts) is central to the AFSC operations, for example, by

1. Informing the structure of models and reports; for example, regarding stock structure, dynamics, mechanistic drivers of productivity and sampling efficiency, and parameter values.
2. Informing survey planning by identifying important mechanisms and ecosystem variables to measure.
3. Providing contextual support and interpretation for trends that are reported to the Council.

Role for condition -- Condition metrics are widely used in process research activities. For example, energetic status is often measured in habitat research to evaluate whether observed differences in habitat suitability translate into a predicted response in fish/crab physiological status. Similarly, monitoring programs collect condition information to interpret and contextualize differences in observed habitat utilization. This information is then used to generate Level-3 maps of essential fish habitat, as stipulated by the most recent Alaska Essential Fish Habitat Research Plan. Differences in prey forage and resulting changes in condition for commercial species have also been invoked to justify ongoing changes in our monitoring programs, for example increased bottom trawling efforts in the northern Bering Sea.

Recommendations

As a result of the workshops and discussions, the Condition Congress Steering Committee (composed of the authors of this report) compiled the following process and research recommendations. We intend these recommendations to apply during three stages of scientific operations:

1. Project design: Researchers might consider these recommendations when deciding between alternative directions for new research, or to pivot existing research towards high priorities.

2. Proposal writing: Researchers might reference these recommendations when writing a proposal, and use that linkage to justify the importance of receiving funds;
3. Proposal evaluation: Reviewers should consider these recommendations when deciding how to allocate funding among different competing proposals.

We note that new topics may arise and be important. Therefore, the list of recommendations is not intended to be static and it will in some cases be important to fund topics that are not explicitly prioritized here.

We have identified four recommendations regarding Intercalibration, Interpretation, the Research Process, and Communication. Each recommendation involves several bullet points that provide specific examples of how these recommendations could be followed. These recommendations apply equally to field, laboratory, and modelling efforts at the AFSC. We also include additional (more specific or lower priority) recommendations as Appendix A.

Intercalibration

We recommend synthesis research to develop and apply methods to intercalibrate and thereby combine easy-to-collect proxies for condition (e.g., morphometrics, fatmeter, GSI/HSI, FT-NIRS) against direct physiological measurements for a given process of interest (which are often expensive, time-consuming, or impossible to measure in the field).

- The appropriate physiological measurement to intercalibrate against will vary based on study goals; for example, energy density to measure prey value as forage, lipid content in energy-storing tissue to measure energetic reserves for reproduction, RNA-DNA ratio and cellular division rate to measure individual growth rates, fatty acids to measure prey contribution to diet, etc.
- This intercalibration should account for seasonal variation and spatially unbalanced designs, and will allow new metrics to be intercalibrated against existing metrics as they are developed.
- The results of this intercalibration will then predict the physiological metrics that would have been measured across space and time had a direct physiological measurement been feasible (with associated estimates of uncertainty).

Interpretation

We recommend development of laboratory experiments, field observations, and population-dynamics models seeking to link direct physiological measurements of condition (e.g., RNA-DNA, energy density) to demographic outcomes, so that condition information can be interpreted as measuring an ecological mechanism.

- Stock assessment models should consider using time-series of these physiological measurements (i.e., resulting from intercalibration) as a covariate, and future ESPs could identify which stock-assessment parameter (e.g., recruitment, weight-at-age, maturity ogive) is most likely to be usefully informed by condition and during which time of year, and for which size-class or cohort.
- Laboratory experiments should seek to measure demographic outcomes from condition states and prioritize those life-stages that are demographic bottlenecks (e.g., larval starvation or reproductive output resulting from energy density and lipid content).
- Field studies should develop designs that can be replicated broadly across space (and time when possible) that can be used to intercalibrate direct physiological measurements and easy-to-collect proxies, and can represent spatial variability; for example, within bioenergetic models.

Research Process

The allocation of limited research funding within AFSC should prioritize research to improve efforts that are currently or close-to-informing management (e.g., cited as support for specific decisions by council bodies) and/or identified as important by Alaska Native communities.

- Field validation of new techniques (FT-NIRS, cellular division rates, etc.) should be conducted using a design that simultaneously intercalibrates them against easy-to-collect proxies that are currently being used for specific species and tracks cohorts through time.
- Laboratory experiments should be directed towards species or guilds where stock assessments have cited a strong need for improved understanding; for example, heatwave impacts on Pacific cod.
- Research to synthesize and intercalibrate condition information should identify specific demographic parameter(s) and stock-assessment collaborators and have a plan to provide the metric in a timely and repeatable manner.

Communication

Condition metrics should be considered for inclusion in stock assessments, ESRs, ESPs, and other venues, while explicitly describing the demographic process that that condition metric is believed to represent in each case and to the extent possible standardizing across species and life-stages.

- We encourage ESR and ESP contributors as possible to use the same mathematical formulation when calculating morphometric condition, ideally after removing the effect of stomach contents, so that users can compare variability across species and life-stages.
- Authors should carefully acknowledge the strengths and limitations when presenting a given metric (e.g., where morphometric metrics confound condition with stomach contents) and explicitly justify why that metric is appropriate for their use.
- The link between condition metrics and demographic processes will in some cases vary among taxa, such that standardized methods are useful in some but not all cases, and researchers should carefully justify when using non-standard calculations or methods.

Conclusions

Condition metrics are widely used at the AFSC, as shown in the Inventory arising from the 2021 Condition Congress (see Table 1). This wide usage arises in part because condition has application within four major mandates (stock assessment, ecosystem status reports, ecological and socioeconomic profiles, and process research). However, our use of condition metrics could be improved by a renewed emphasis on intercalibrating multiple metrics, improved physiological interpretation, refinements to our research process, and improved communication between research groups.

Acknowledgments

We thank all of the many presenters and attendees for the Condition Congress workshops. We also thank K. Shotwell for providing helpful comments during writing.

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Table 1 -- Inventory of condition metrics presented and discussed during the Condition Congress, listing the Category (see Background section for definitions), the indicator used, the analytical technique applied to measure it, the life-stages studied, the time over which the indicator integrates when measured using a given analytical technique, the benefits and limitations of such an approach, the external inputs and/or data used for validation and calibration, as well as details regarding its current use at the AFSC (to fit on page, the table is broken into two parts).

Entry number	**Category**	**Indicator**	**Technique**	**Life stages (current application)**	**Integration time (shorter end of spectrum)**
1	1 - condition	Morphometric condition	Deviations from len-wt relationships (Fulton's K-like)	Sub-adult, Adult	Months
2	1 - condition	Morphometric condition	Deviations from len-wt relationships (Fulton's K-like)	Sub-adult, Adult	Months
3	1 - condition	Morphometric condition	Deviations from len-wt relationships (Fulton's K-like)	Age-0	Months
4	1 - condition	Morphometric condition	Body shape measures from at-sea photos	Age-0	Months
5	1 - condition	Energy density	Bomb calorimetry of individual/pooled specimens	Juvenile	Months
6	1 - condition	Proximate composition	Measurement of %lipid, water, protein	Juvenile	Months
7	1 - condition	Total lipids	Latroscan, Gravimetric, or SPV method	Eggs to adults (tissue specific for larger sizes)	Months
8	1 - condition	Lipid classes	Iatroscan	Eggs to adults (tissue specific for larger sizes)	Months

9	1 - condition	Fatty acid composition	Gas chromotography	Eggs to adults (tissue specific for larger sizes)	Months
10	1 - condition	Percent lipid composition	Fat meter (based on lipid/water ratio)	Juvenile to adult (can be tissue specific)	Months
11	1 - condition	Percent lipid composition	Bio-electrical impedance (BIA) (based on lipid/water ratio)	Juvenile to adult (can be tissue specific)	Months
12	1 - condition	Percent lipid composition	FT-NIRS (absorbance spectrum of different chemical bonds)	Eggs to adults (tissue specific for larger sizes)	Months
13	1 - condition	Relative condition (Kn)	Deviations from len-wt relationships (Fulton's K-like)	Sub-adult, Adult	Months
14	1 - condition	Standardized weight	Deviations from len-wt relationships (Fulton's K-like)	Sub-adult, Adult	Months
15	2 - growth	Length-at-age	Means of aged-individuals	Age 0-3	Lifetime
16	2 - growth	Length-at-age	Otolith increment widths	Juvenile	Lifetime
17	2 - growth	RNA/DNA	RNA/DNA measures of muscle tissue	Juvenile	~ 1 week
18	2 - growth rate	Weight at age	Means of aged-individuals	Juvenile (age 1+), Adult	Annual
19	2 - growth rate	Cell cycle analysis	Flow cytometry of muscle tissue determines fraction of cells undergoing division	Larvae	Days
20	3 - prediction	Growth rate potential	Bioenergetic model	Juvenile	Days-Weeks
21	3 - prediction	Growth potential	Bioenergetics model estimates	Juvenile to Adult	Weeks to year?

Table 1. -- Continued.

Entry number	Benefits	Limitations	External inputs, validation, or calibration	Species applied to	Time series availability	Application	PI
1	Common application, timeliness, widespread availability	Ecological interpretation, representative sampling (spatial/temporal)	none	multiple groundfish	Existing time series from groundfish surveys	RT, ESR, ESP	Sean Rohan
2	Common application, timeliness, widespread availability	Ecological interpretation, representative sampling (fishery-dependent sampling)	none	sablefish	Existing time series from fisheries	RT, ESP (as economic indicator)	Jane Sullivan
3	Common application, widespread availability, seasonal correction	Ecological interpretation, representative sampling (spatial), measured in lab (no at-sea collection)	Interpretation improved with calibration to other condition metrics	GOA walleye pollock	Time series 2000-2019 (odd years)	included in ESR & pollock ESP	Lauren Rogers
4	Timeliness (can measure at sea)	Not yet validated in relation to other metrics	Requires calibration to other condition metrics	GOA walleye pollock	NA		Alison Deary
5	Universal application; common "currency" for	Moderate throughput (~60 samples/week); seasonal/ontogenetic patterns		Fish, zoop, inverts etc, for species specific; walleye	2003-2019 Bering age-0 pollock; 1997-2019 BS salmon; 2006-	ESR for prey field energy content; ESP pollock age-0	Johanna Vollenweider

	predators and prey			pollock & pacific cod for spatial/temporal variation	2019 SEAK herring; selected years Arctic spp.	recruitment indicator	
6	Focus on energy storage, common interpretation	Moderate throughput; additional lab processing	Can be linked to external reference points, e.g., starvation threshold. Assumption of storage depot	Fish, zoop, inverts etc, for species specific patterns	na	Process research	Johanna Vollenweider
7	Focus on energy storage, common interpretation	Calibration and processing time (improved with SPV)	SPV being validated for marine organism groups	Gadids, flatfishes, crabs, zoopl.	Multi-year gadids+zoopl in Chukchi + targeted collections	EFH assessment & process research	Louise Copeman
8	Refined description of storage vs structure components	Calibration and processing time	May require source-specific standards.	Gadids, flatfishes, crabs, zoopl.	Multi-year gadids+zoopl in Chukchi + targeted collections	EFH assessment & process research	Louise Copeman
9	Also provides information on food web tracers and essential nutrients	Interpretation of food web lingages in complex food webs	GCMS can imporve rare peack identification, improve interpretation.	Gadids, flatfishes, crabs, zoopl., phytopl.	Multi-year gadids+phytopl in Chukchi + crab in Bering	EFH assessment & process research	Louise Copeman
10	Increased sample rate, can be	Precision not clear; requires technique standardization	Calibration to more precise measures to	Gadids	na: Initial comparision	EFH assessment & process	Bianca Prohaska

	performed in the field; not sensitive to stomach fullness		increase reliability & interpretation		and validation study underway	research; potential ESP	
11	Increased sample rate, can be performed in the field; not sensitive to stomach fullness	Precision not clear; requires technique standardization	Calibration to more precise measures to increase reliability & interpretation	testing with gadids	na: Initial comparision and validation study underway	EFH assessment & process research; potential ESP	Johanna Vollenweider
12	Increased sample rate, can be performed in the field	Requires calibration to reference tissue standards; evaluation of error sources; requires technique standardization	Calibration to more precise measures to increase reliability & interpretation	testing with gadids	na: Initial comparision and validation study underway	EFH assessment & process research; potential ESP	Esther Goldstein
13	Common application, widespread availability, seasonal correction	Ecological interpretation, representative sampling (spatial), measured in lab (no at-sea collection)	Interpretation improved with calibration to other condition metrics	Atka mackerel	Partial sime series since 1998	EFH assessment & process research; potential ESP	Morgan Arrington
14	Common application, timeliness, widespread availability	Ecological interpretation, representative sampling-fishery dependent	none	EBS walleye pollock	Annually	WP stock assessment as related to fishery yeild	Jim Ianelli
15	Common interpretation,	Processing time; representative sampling (unbalanced	Aging had been validated	Bering yellowfin sole and	na - due to limited series	EFH assessment & process	Cynthia Yeung

	availability for aged species.	spatio-temporal sampling)		northern rock sole	and spatial variation	research - fishery productivity in northern BS	
16	Common interpretation, availability for aged species.	Processing time; representative sampling (unbalanced spatio-temporal sampling)	Aging had been validated	Northern rock sole, yellowfin sole	Annual collections in different regions of the Bering	EFH assessment & process research - fishery productivity in northern BS	Cynthia Yeung
17	Short response links observed growth to sampled environmental/ habitats	Reflects accumulation of protein formation aspects of growth (not lipids). Requires calibrations for species and stages.	Relative measure, but can be quantitively calibrated to growth rate with lab experiments.	Pacific herring, gadids, salmonids, forage species	Multi-year for herring + gadids; limited for others	EFH assessment & process research	Fletcher Sewall
18	Common interpretation, availability for aged species	Attribution (correlation/covariati on across years)	Aging had been validated	walleye pollock	Existing time series - since 1999 Bering	Process research (age-specific climate impacts on growth)	Krista Oke & Mike Litzow
19	Direct measure of physiological process	Limited throughput; field preservation (-80C); laboratory processing; applied precision limited to categorical	Species-specific calibration, ontogeny effects?	walleye pollock	Time series 2007-2019 GOA + Bering	Process research (link larval performance to env conditions)	Steve Porter

		healthy/starving (improved?)					
20	Spatially explicit	Unknown params (e.g., activity). Prediction not "traceable" to samples	model calibration; data availability of prey abund & energy density	sockeye salmon	Potential for hindcast & forecast (with assumptions)	EFH assessment & process research	Ed Farley
21	Can integrate multiple types of environmental factors: temp, prey avail., energy density, distribution	Growth potential not realized growth; Data not available at same time/space scales; not ground-truthed to observations.	Requires fish size, diet data, prey availabilty, metabolic rate data, prey energy density.	walleye pollock, Pacific cod, Pacific halibut, arrowtooth, sablefish, rockfish	Annually in fall?	ESR, ESP, EFH assessment & process research	Kirstin Holsman

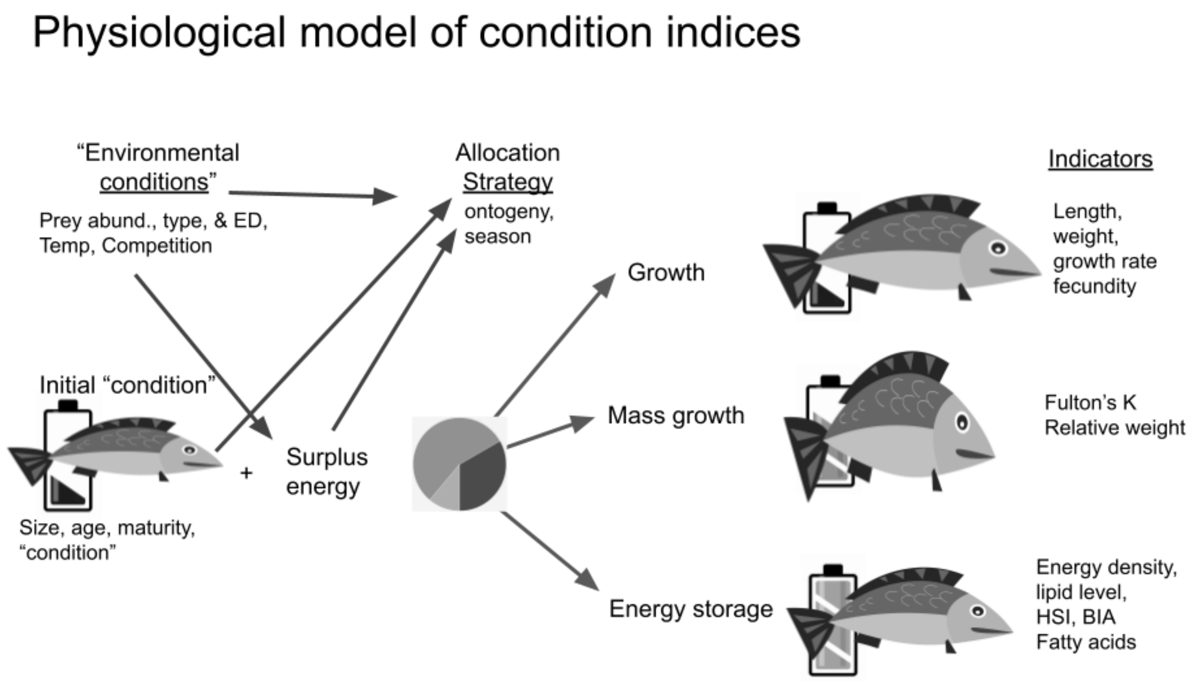

Figure 1. -- Condition metrics reflect aspects of the state of an organism. Those state variables are influenced by the interaction of external environmental factors and internal physiological process which regulate the allocation of energy between somatic growth, energy storage, and reproduction.

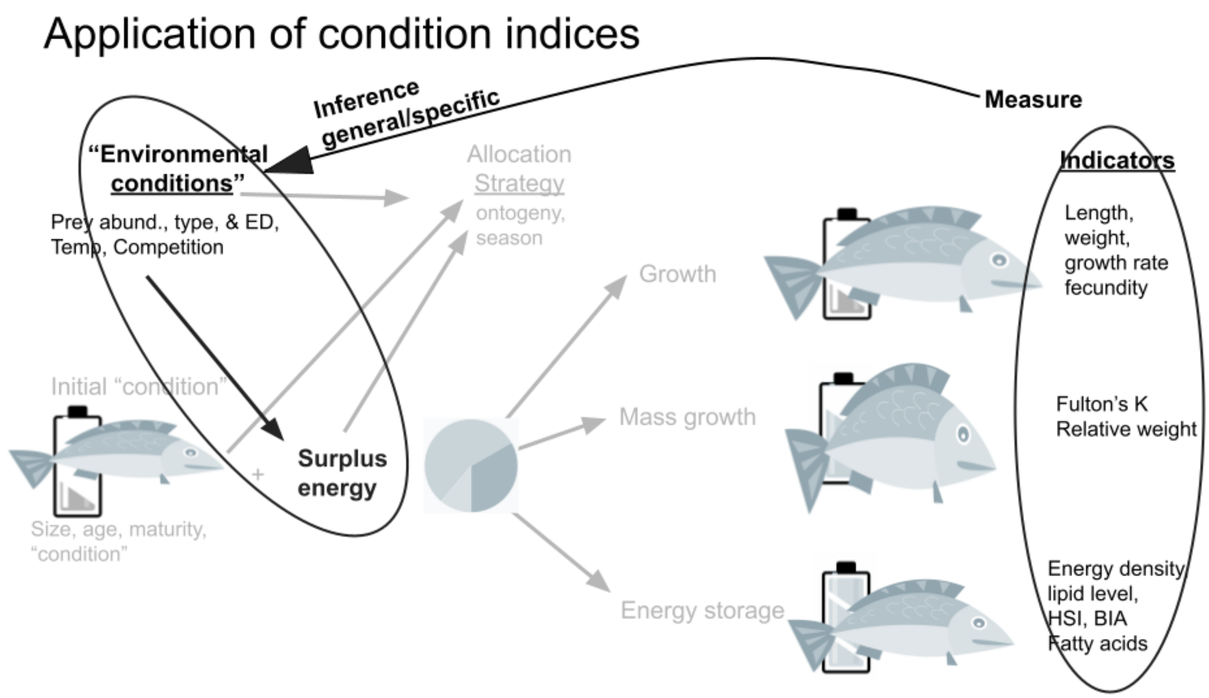

Figure 2. -- Condition indices are commonly applied in fisheries science to make inferences about the influence of environmental factors (and their effect on available energy) on the productivity of fishery resources.

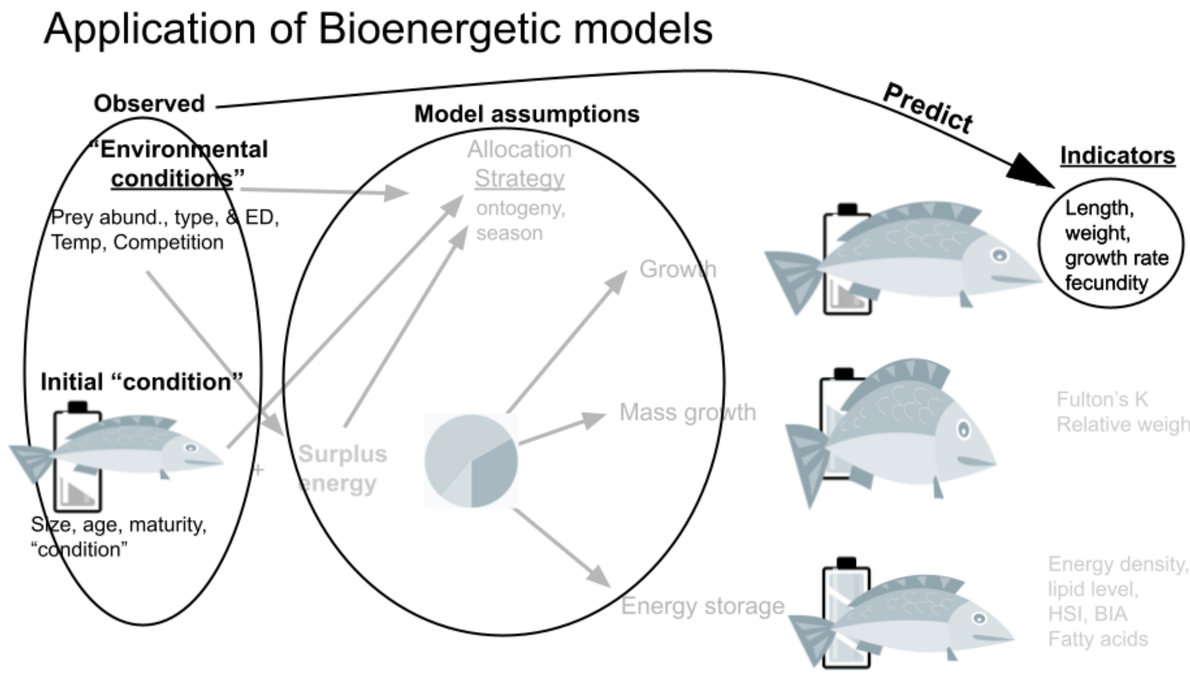

Figure 3. -- Bioenergetic models of growth use information on environmental conditions to predict changes in the state of organisms (most often body size) based on independently derived parameterizations of physiological processes and assumptions of energy allocation strategies.

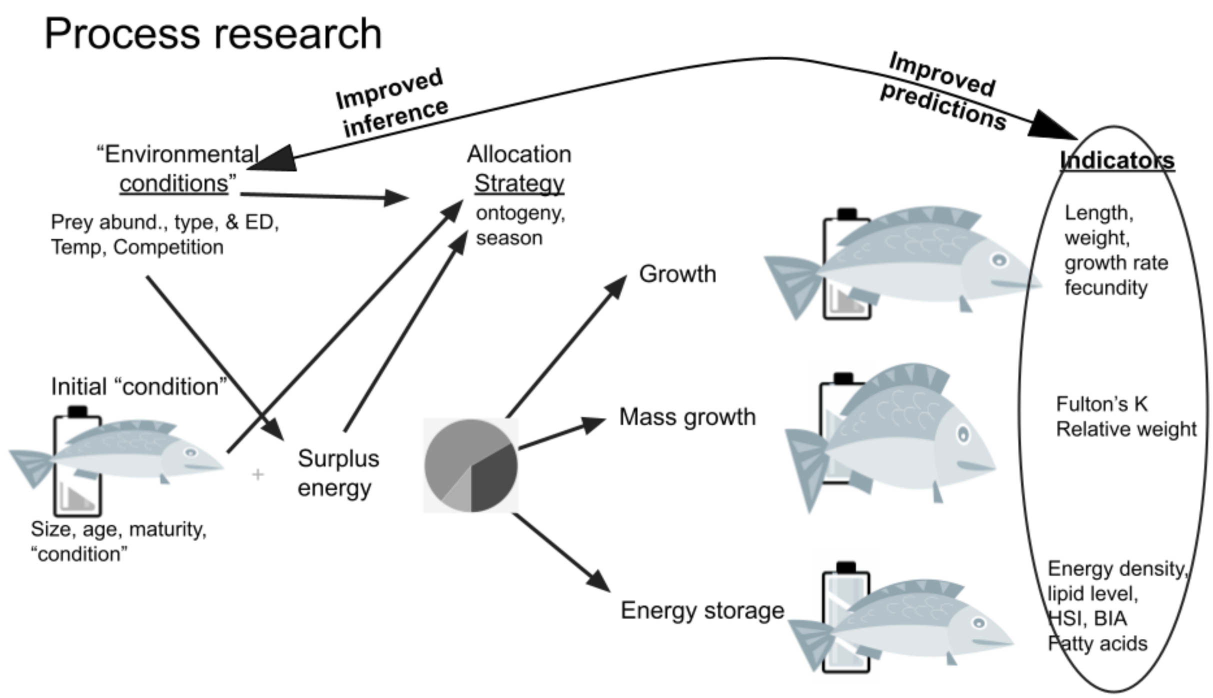

Figure 4. -- Process research examines the relationships between environmental factors, surplus energy, and allocation strategies to improve the inferences made from field measures of condition indices and the prediction of productivity from environmental conditions.

Appendix

Additional Recommendations

During the Condition Congress, we identified a wide range of recommendations. Some of these were unanimous and broadly relevant -- these we included as the four recommendations in the main text. Other recommendations were more narrowly focused, either taxonomically or in terms of analytical methods. We include those here, and still encourage coordinated research along these lines.

- *Crab condition:* Developing condition metrics for crabs is a high priority; for example, to understand the likely causes and consequences of smaller size-at-maturity for snow crab in northern habitats in the Bering Sea and southern Chukchi Sea.
- *Standardizing bioenergetics*: We recommend clarifying and standardizing the development and interpretation of bioenergetic modelling estimates of growth potential. This includes clarifying which factors are included: temperature, predator energy density, prey energy density, consumption rates, and prey availability – all of which are potentially available, but not at the same spatial/temporal scale and not at the same time. For example, temperatures are available immediately, while

energy density and other metrics take time to process, consumption rates are assumed to be maximal but not measured/estimated. These specific assumptions are not uniformly communicated across bioenergetic applications.

- *Tracking cohorts*: We recommend standardizing methods so that we can track interannual variation in condition across cohorts; for example, linking condition for larvae/juveniles with subsequent condition of adults. This will likely require improved coordination among programs, as well as improvements in intercalibrating condition measurements to compare the different types of measurements that are typically available for larvae, juveniles, and adults.
- *Emphasize spatial and temporal variation*: Research and operational use of condition for Ecosystem Status Reports (ESRs) and Ecosystem and Socioeconomic Profiles (ESPs) has focused on temporal variation in condition metrics. However, habitat and process research would both benefit from a similar emphasis on spatial variation. We recommend that any project developing either spatial or temporal indices should consider whether they can produce both and thereby increase their management relevance.
- *Clarity of communication*: We recommend that condition metrics be accompanied by clear statements on how they should be interpreted, as well as listing potential limitations to avoid confusion, misunderstanding, and misrepresentation.

- *Morphometric condition*: We recommend future research and operations to account for stomach fullness prior to calculating morphometric condition, so that variable stomach-fullness is not confused with variable energy reserves (e.g., by linking age-length-weight records to stomach content records and pre-processing weight to subtract out measured or predicted stomach contents). Secondarily, we recommend that Fulton's K be replaced with Le Cren’s condition, to account for the typically allometric relationship between animal length and volume.

U.S. Secretary of Commerce
Gina M. Raimondo

Under Secretary of Commerce for Oceans and Atmosphere
Dr. Richard W. Spinrad

Assistant Administrator, National Marine Fisheries Service. Also serving as Acting Assistant Secretary of Commerce for Oceans and Atmosphere, and Deputy NOAA Administrator
Janet Coit

September 2021

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National Marine Fisheries Service
Alaska Fisheries Science Center
7600 Sand Point Way N.E.
Seattle, WA 98115-6349