A Bioenergetics Model for Pacific Halibut Reveals the Potential for Bottom-Up Controls on Growth and Size-at-Age.

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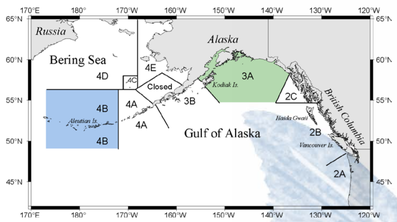

Figure 1. Map of International Pacific Halibut Commission management areas.

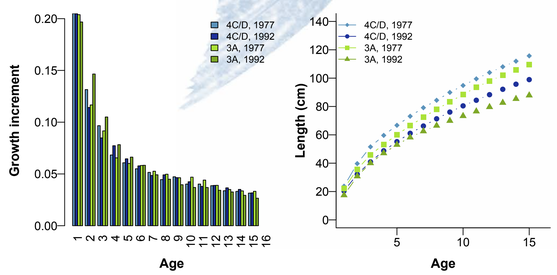

Figure 2. Growth increments based on Pacific halibut otoliths from fish in 4C/D and 3A born in 1977 and 1992 (left) and estimated length at age based on otoliths growth increments and capture length (right).

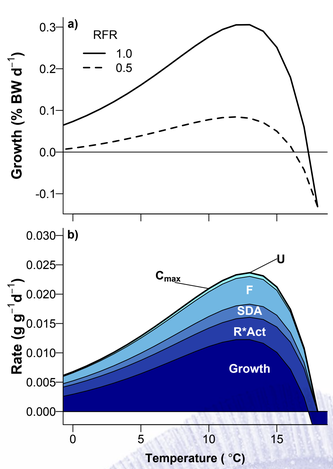

Figure 3. Pacific halibut bioenergetics model specific growth rates as a function of temperature and relative foraging rate (RFR; a). Specific bioenergetic rates as a function of temperature (b). Rates are for an 8 kg fish.

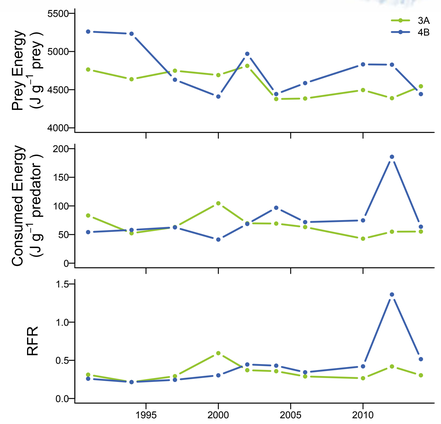

Figure 4. Top: Mean energy density of prey found in stomachs of Pacific halibut from areas 3A (n= 250) and 4B (648). Middle: Mean daily rations based on stomach analyses. Bottom: Relative foraging rate (RFR) based on stomach analyses and bioenergetics model estimates of maximum consumption rate.

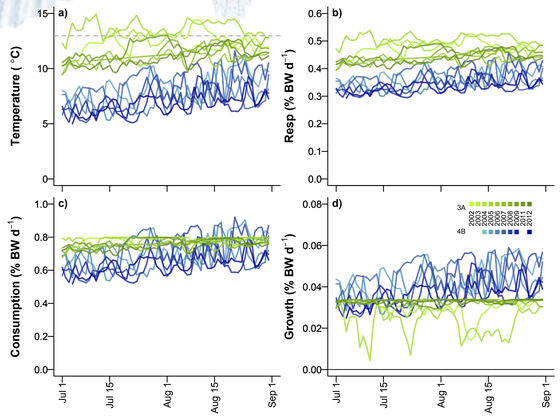

Figure 5 Simulated bioenergetics rates between 3A and 4B management areas for an 8 kg fish. Observed summer temperatures at 4B (blue lines) and 3A (green lines; a), area-specific bioenergetics simulated metabolic demand (b), consumption rates (c), and growth (d).

Table 1. Pacific halibut bioenergetics model equations.

Definition	Equation	Eq.
Modeled growth	$\hat{G}_d = \left(C_d - (R_d \cdot ACT + SDA_d + F_d + U_d)\right)\frac{E_{fish}}{E_{prey}}$	T1.1
Consumption	$C_d = C_d^{max} \cdot f(T) \cdot P_y$	T1.2
Modeled weight	$\hat{W}_d = \hat{G}_d + \hat{G}_d \cdot \hat{W}_{d-1}$	T1.3
Maximum consumption	$C_d^{max} = C_A \hat{W}_{d-1}^{R_B}$	T1.4
Temperature scaling function	$f(T) = V^X \cdot e^{X(1-V)}$	T1.5.1
	$X = \frac{Z^2 \cdot \left(1 + \left(1 + \frac{40}{Y}\right)^{0.5}\right)^2}{400}$	T1.5.2
	$V = \frac{T_{cm} - T}{T_{cm} - T_{co}}$	T1.5.3
	$Z = ln(Q_c) \cdot (T_{cm} - T_{co})$	T1.5.4
	$Y = ln(Q_c) \cdot (T_{cm} - T_{co} + 2)$	T1.5.5
Respiration	$R_d = R_A \hat{W}_{d-1}^{R_B} \cdot e^{Q_R T} \cdot \frac{E_{O_2}}{E_{prey}} \cdot Act$	T1.6
Specific dynamic action	$SDA_d = S_A(C - F)$	T1.7
Egestion	$F_d = F_A C$	T1.8
Excretion	$U_d = U_A(C - F)$	T1.9

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Abstract:

With a maximum weight of more than 500 pounds and maximum length of over 8 feet, Pacific halibut (*Hippoglossus stenolepis*; hereafter "halibut") are ecologically, commercially, and culturally one of the most important Alaskan groundfish species. However, recent stock assessments found declining trends in halibut biomass over the last decade. Potential drivers of low biomass vary regionally but include climate, trophic, and fishery effects on growth that have influenced recent declines in mean size-at-age over the past two decades (>50% in some cases). Changes in size-at-age can arise from a variety of physical, ecological, and fishery effects (as well as aging and sampling artifacts) including size-dependent fishery or predation mortality, alteration in growth from variability in prey quality or quantity, and changes in temperature-dependent metabolic demands. Spatial variability in mean size-at-age has been documented for halibut across International Pacific Halibut Commission regulatory areas (Fig. 1) and regional contrast in size-at-age and climate and trophic conditions provides a unique opportunity to use a bioenergetics model to evaluate the effects of changes in diet and thermal experience on potential growth rates. Here we apply a recently developed bioenergetics model for Pacific halibut to survey-based diet and temperature data for Alaska and discuss the potential for spatial variability in size-at-age to have arisen from physical- and trophic-driven changes in growth.

Methods:

- We parameterized a bioenergetics model for Pacific halibut using previously reported rates for allometric- and temperature-specific prey consumption (Paul et al. 1994, Hurst 2004), respiration (Auchterlonie 1998), activity (Stoner etal. 2006), and waste (Auchterlonie 1998; Table 1).
- Stomach samples from Pacific halibut collected between 1991 and 2014 in 3A (n= 250) and 4B (648) were used to determine the mean energy density of halibut prey, and the mean relative foraging rate (RFR) of fish in each area.
- Using observed RFR and prey energy densities, the bioenergetics model was then applied to available data from two NOAA mooring buoys in halibut management areas 3A (buoy 46080) and 4B (buoy 46071) for the years 2002-2011 and for a simulated 8 kg fish foraging during summer months.
- Results were compared to patterns in growth observed from otoliths collected in each area in 1977 and 1992.

Results:

- Otolith analyses show a decline in Pacific halibut size-at-age between 1977 and 1992, with larger Pacific halibut found in the western Aleutian Islands (4B) than east (3A; Fig. 2).
- Differential length at age begins early in the life history, with size at age 0 setting the growth trajectory for fish (Fig. 2; right).
- Temperature in the west (4B) may be more favorable for summer growth as conditions in the east (3A) often approach or exceed thermal optimum. (Figs. 3 and 5).
- Halibut in 3A also exhibit lower relative foraging rates (RFR) and consumed prey that had slightly lower energetic value than prey in 4B (Fig. 4)
- Bioenergetics modeling revealed that reduced foraging efficiency, increased metabolic demand, and reduced prey quality further contribute to reduced growth and size-at-age for Pacific halibut. (Fig. 4).

Conclusion:

Although early life-history growth may set up the growth trajectory of fish in each area, increased temperature-driven metabolic demands and reduced prey quality and availability further limit opportunities for compensatory growth in populations of halibut from management areas 3A. Thus we find support for environmentally driven spatial changes to growth that may impact halibut size-at-age.

References

- Auchterlonie, N. 1998. Oxygen consumption and bioenergetics of the Atlantic halibut (*Hippoglossus hippoglossus* L.): Implications for culture. PhD Thesis. Institute of Aquaculture, University of Stirling, United Kingdom.
- Hurst, TP. 2004. Temperature and state-dependence of feeding and gastric evacuation in juvenile Pacific halibut. Journal of Fish Biology 65:157-169.
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- Stoner, A, ML Ottmar, and TP Hurst. 2006. Temperature affects activity and feeding motivation in Pacific halibut: Implications for bait-dependent fishing. Fisheries Research 81:202-209.

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