Environmental windows for small pelagic fish in the western North Pacific: How do their vital parameters respond to climate variability and change?

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Hiroshima, Japan, October 12–21, 2012
Invited talk, Session 3 (S3-8802), October 18 (Thursday)
“This session brings together researchers of marine ecosystems, physical oceanography and climate to share ideas about what physical parameters and processes are important in understanding and predicting the response of specific marine ecosystems to climate forcing.”
Role of this talk

Environmental windows for small pelagic fish in the western North Pacific: How do their vital parameters respond to climate variability and change?

Objective is to show …

1. How dramatically environmental variability could regulate survival probability of small pelagic fish
   • Introducing the “growth–survival” paradigm

2. How differently the similar environmental condition could affect the population dynamics of different species.
   • Reviewing several hypotheses
   • Comparing responses of vital parameters to environmental factors among multi-species
Long-term landing histories of small pelagic fish in waters around Japan in response to Pacific Decadal Oscillation (PDO).
Species alternations

Four different current systems

- Anchovy *Engraulis* spp.
- Sardine *Sardinops* spp.

The patterns of species alternations tended to be synchronous among the Pan-Pacific regions and asynchronous between the Pan-Pacific regions and the Benguela region.
Key questions

Why do even subtle environmental changes sometimes trigger dramatic alternations?

Why do anchovy flourish and sardine collapse or *vice versa* under the same ocean regime?

Concept:
Differential responses of vital parameters to environmental factors constitute a key to understand biological processes linking climate variability to species alternations.
Takasuka et al.

**Cascade**

**Input**
- Climate change
- Ocean regime
- Predator field

**Output**
- Mortality rate

**“Growth–survival” paradigm** in early life stages

- Growth rate = survival potential

**Amplifier**
- Growth rate
- Spawning
- Condition etc.

**Other**
- Fishing

**Vital parameters**
- Predation rate

**Physical factors**
- Transport/migration

**Biological factors**
- Vital parameters
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**Paradigm/mechanisms**

**“Growth–survival” paradigm in early life stages**

Larger and/or faster growing individuals are more likely to survive than smaller and/or slower growing conspecifics.

**Functional mechanisms**

Why do they survive better?

I. **“Bigger is better”** (Miller et al. 1988)

Growth rate determines somatic size influencing survival advantages.

II. **“Stage duration”** (Chambers & Leggett 1987, Houde 1987)

Growth rate determines high mortality larval stage duration.


Growth rate *per se* exerts direct impacts on predation mortality.

What’s the consequence of environmental variability?
Consequence of 2ºC change

Relationship of growth rate to temperature for Japanese anchovy larvae.
Stage duration mechanism

**Growth decline:**
31% of the range

**Metamorphosis:**
6.5 days delay

**Assuming mortality rate:**
= 30% day\(^{-1}\)

**survival rate:**
= 70% day\(^{-1}\)

\((0.70)^{6.5} = 0.098\)

**Cumulative survival probability during larval stage:**
multiplied by 9.8%

9.8% against 100%

**Consequence of 2ºC change:**
ca. 10 times difference in survival probability

**Size-at-age of the metamorphosing larvae vs non-metamorphosing larvae of Japanese anchovy.**

Takasuka *et al.* (2004) *MEPS*
Field sampling

- Japanese anchovy larvae and their potentially predatory fish were captured simultaneously by the same tows of a trawler in a coastal fishing ground.

Growth comparison

- Ingested larvae
- The larvae actually ingested by the predators

- Original larvae
- The surviving larvae from the original populations

Takasuka et al. (2003, 2004a,b, 2007) MEPS
Example of comparison of growth rate on standard length between ingested larvae and original larvae.

Takasuka et al. (2003) MEPS

This is the clearest example. The similar results were obtained from 3 of 5 samples.
Frequency distributions of growth rate compared between ingested larvae and original larvae with an index of relative predation mortality.

Predators:
- Pacific round herring
- Japanese jack mackerel

Growth decline:
- 0.20 mm day\(^{-1}\)
- (0.50 to 0.30 mm day\(^{-1}\))

Predation mortality ratio increased from 0.5 to 2.5

Instantaneous predation mortality multiplied by ca. 5 times
Takasuka et al.

Input

- Climate change
- Ocean regime
- Predator field

Output

- Mortality rate

“Growth–survival” paradigm in early life stages: Growth rate = survival potential

Amplifier

- Growth rate
- Spawning
- Condition etc.

Vital parameters

- Physical factors
- Biological factors
- Predation rate
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Small pelagic fish in the Kuroshio Current system
Long-term landing histories of small pelagic fish in waters around Japan in response to Pacific Decadal Oscillation (PDO).
Optimal growth temperatures

Relationship between recent 3-day mean growth rates and sea surface temperature for anchovy and sardine larvae (Takasuka et al. 2007 CJFAS).

16.2°C

22.0°C

Anchovy

Sardine
Conceptual framework of the “optimal growth temperature” hypothesis (Takasuka et al. 2007 CJFAS).
Similarities and differences in spawning temperature patterns represent those in the long-term population dynamics (Takasuka et al. 2008 MEPS).
Temperature & Food

Contrasting responses in larval and juvenile growth to a climate-ocean regime shift between anchovy and sardine

2009 in CJFAS

Motomitsu Takahashi, Yoshiro Watanabe, Akihiko Yatsu, and Hiroshi Nishida

Relationships of growth rates to temperature and prey density for **anchovy** and **sardine** larvae and early juveniles in the Kuroshio–Oyashio transition region (Takahashi et al. 2009 CJFAS).
Takasuka et al.  

Trophic dissimilarity

Cool regime
- Intermittent mixing (upwelling, cool)
  - Larger-cell (diatom)
    - High biomass
  - Larger copepods
  - Particulate-feeder favored

Warm regime
- Physical forcing (wind, etc.)
  - Water column (temperature)
    - Phytoplankton community
    - Zooplankton community
    - Pelagic fish community
  - Highly stable (warm)
    - Smaller cell (flagellate)
      - Low biomass
    - Smaller copepods
    - Filter-feeder favored

Conceptual framework of the “trophic dissimilarity” hypothesis from the Benguela Current system (van der Lingen et al. 2006 AJMS).

Anchovy ← Differential feeding strategies → Sardine
Gill raker morphology also differed between anchovy and sardine in the Kuroshio Current system. However, there were not great differences in feeding habit during the early life stages.

Feeding habits of larvae and juveniles in Tosa Bay.
Okazaki, Y., Kubota, H. et al.

Tanaka et al. (2006) JFB
van der Lingen et al. (2009) SPACC book
Strong trophic overlaps throughout the life histories among the species.

We conclude that anchovy and sardine are ecologically congeneric species in terms of trophic position in this region.
Population decline of the Japanese sardine, *Sardinops melanostictus*, in relation to sea surface temperature in the Kuroshio Extension

Masayuki Noto and Ichiro Yasuda

1999 in CJFAS

Kuroshio Extension and its southern recirculation area (KESA)

Cooler: lower mortality = higher survival
Warmer: higher mortality = lower survival

SST anomaly
Mortality coefficient anomaly

Relationships of natural mortality coefficient anomaly from postlarva to age 1 to February SST (left) and February SST anomaly (right) in KESA for Japanese sardine (Noto & Yasuda 1999 CJFAS).
Japanese sardine (*Sardinops melanostictus*) mortality in relation to the winter mixed layer depth in the Kuroshio Extension region.

![Graph showing mixed layer depth and mortality coefficient anomaly](image)

Mixed layer depth

Natural mortality coefficient anomaly from postlarva to age 1 of Japanese sardine vs February/March mixed layer depth, and spring phytoplankton density vs March mixed layer depth (Nishikawa & Yasuda 2008 FO).

![Graph showing spring phytoplankton density vs March mixed layer depth](image)

Spring phytoplankton density vs March mixed layer depth

\[ y = 0.26x + 1.92 \]

south-KE, \( r = -0.88 \) (\( P < 0.001 \))

2008 in FO

**Title**

Winter mixed layer depth
Impact of winter-to-spring environmental variability along the Kuroshio jet on the recruitment of Japanese sardine (*Sardinops melanostictus*)

HARUKA NISHIKAWA,† ICHIRO YASUDA AND SACHIHIKO ITOH

2011 in FO

- Ocean general circulation model for the Earth Simulator (OFES)
- “Kuroshio axis coordinates”

Time series data of survival index (ln-transformed recruitment per spawning stock biomass: LNRPS) for Japanese sardine and February mixed layer depth around the Kuroshio axis (Nishikawa et al. 2011 FO).
Trophodynamics hypothesis in the Kuroshio Current system (keys: winter mixed layer depth & spring plankton bloom in the nursery grounds).
Species alternation

**Maximum biomass & Extent of fluctuation:** 1 order difference

Long-term landing histories of small pelagic fish in waters around Japan in response to Pacific Decadal Oscillation (PDO).
Examples of monthly egg abundance distributions of anchovy and sardine in the western North Pacific (Takasuka et al. 2008 MEPS).
Transport and environmental temperature variability of eggs and larvae of the Japanese anchovy (*Engraulis japonicus*) and Japanese sardine (*Sardinops melanostictus*) in the western North Pacific estimated via numerical particle-tracking experiments.

Considering differences in spawning seasons/grounds

Interannual variations of mean temperatures experienced during the transport processes

Numerical particle-tracking experiments to examine the transport and variability in environmental temperature experienced by eggs and larvae of anchovy and sardine (Itoh *et al.* 2009 FO).
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Egg survey data set
A long-term data set of monthly egg surveys

- Off the Pacific coast of Japan
- Last 30 years (1978–2007)
- Vertical tows of NORPAC net
- 114,130 samples

Sampling stations in the monthly egg surveys off the Pacific coast of Japan from 1978 to 2007 (Oozeki et al. 2007 CalCOFI, Takasuka et al. 2008 MEPS).
GAMs

Spawning responses to multiple environmental factors

Generalized additive models (GAMs) were fitted to egg presence/absence (1/0) data with multiple variables.

Physical factors
- Sea surface temperature (°C): \( \text{SST} \)
- Sea surface salinity: \( \text{SSS} \)

Biological factors
- Zooplankton volume (ml m\(^{-2}\) or μg m\(^{-3}\)): \( \text{PL} \)
- Chlorophyll-a concentration (mg m\(^{-3}\)): \( \text{CH} \)

GAMs with multiple explanatory variables:
\[
y = \alpha + s(\text{SST}) + s(\text{SSS}) + s(\ln(\text{PL})) \text{ or } s(\ln(\text{CH}))
\]
- \( y \): the estimated probability of egg occurrence from 0 to 1
- \( \alpha \): an intercept term
- “s”: an unique smooth term of thin plate regression spline base
Effects of physical factors on spawning probability by the GAMs applied to egg occurrence data (1/0).
Effects of **biological** factors on spawning probability by the GAMs applied to egg occurrence data (1/0).
Energy allocation strategies for reproduction are viewed as a continuum between “income” and “capital” breeders.

“Income breeders”
- Expend energy recently acquired for reproduction
- During spawning, ...
  - Spawn more with food
  - Keep feeding
  - Conditions do not dramatically change

“Capital breeders”
- Expend energy stored over long periods for reproduction
- During spawning, ...
  - Spawn irrespective of food
  - Stop feeding
  - Conditions dramatically decline

Anchovy (*E. japonicus*)
- Spawning probability increased monotonically with food availability.

Sardine (*S. melanostictus*)
- Spawning probability increased with food availability up to some extent but not at higher values.

On a continuum between “income” and “capital”
- Income breeder
  - Anchovy (*E. japonicus*)
- Capital breeder
  - Sardine sardine (*S. melanostictus*)
Temperature–salinity space

Effects of physical factors on spawning probability by the GAMs applied to egg (or larval) occurrence data (1/0).
Energy allocation strategy

Small pelagic fish categorized by energy allocation strategy
Almost “income”:
• Anchovy
• Mackerel
• Jack mackerel
More “capital”:
• Sardine
• Round herring

Effects of zooplankton volume on spawning probability by the GAMs applied to egg occurrence data (1/0).
Takasuka et al.

Summary & Future

Summary
1. How dramatically environmental variability could regulate survival probability of small pelagic fish
   - Vital parameters serve as an amplifier linking environmental variability to dramatic survival variability.

2. How differently the similar environmental condition could affect the population dynamics of different species
   - Species-specific environmental windows would constitute a key to understand mechanisms of species alternations through differential climate effects on different species.

Future
- Different hypotheses should be synthesized in the future.
- Interspecific and intersystem comparisons
- Interdisciplinary collaboration
SUPRFISH

Studies on Prediction and Application of Fish Species Alternation (SUPRFISH)
Leader: Saito, H. (FRA)
Period: 2007–2012

- Interdisciplinary project including 60 scientists
- 4 major themes
  1. Physical oceanographic variations
  2. Lower food-web structure
  3. Physiological and ecological factors of fish
  4. Modeling approaches to species alternations and fisheries management.
Forage fish interactions: Creating the tools for ecosystem based management of marine resources

**November 12–14, 2011, Nantes, France**

Conveners: Stefan Neuenfeldt (DK), Myron Peck (DE), Tim Essington (US), Niels Vestergaard (DK), and Vladimir Radchenko (RU)

The overall keynote will be given by Jake Rice, Canada, on Challenges and Opportunities for forage fish management in the first half of the 21st century. Five theme sessions will be convened that will open with an invited, keynote presentation:

- **Climatic and biotic mechanism forcing on forage fish population recruitment**
  (Key note: Akinori Takasuka, Japan)

- **Post recruitment predator-prey dynamics in ecosystems world-wide**
  (Key note: Geir Huse, Norway)

- **Linking biology and economics**
  (Key note: Røgnvaldur Hannessson, Norway)

- **Ecosystem-based management**
  (Key note: Jason Link, USA)

- **Comparisons between ecosystems and generic properties**
  (Key note: Jeremy Collie, USA)

Finish

Thank you

Thank you for your attention.