Spatial and temporal variations in the recruitment of Japanese eel (A. japonica) in Taiwan

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Outline of the presentation

1. Glass eel crisis for aquaculture in Taiwan
2. Basic biology of glass eel such as
   2.1. Classification and identification
   2.2. Species composition, why different between eastern and western coasts of Taiwan?
   2.3. Upstream migration timing and environmental cues
3. Stock assessment by exploitation rate, YPR and SPR
4. Climate change effect on the recruitment of glass eel
5. Discussion and conclusion
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Fig. 4-1. Eel culture production in Taiwan.
Supply of glass eel is lower than demand in Taiwan

Glass eel shortage problem is very serious in Taiwan!

Mean annual demand (年平均入池量): >20 ton

Mean annual catch (年平均捕撈量): <10 tons
## Statistics of the Glass eel for aquaculture among countries, 2006-2012,

<table>
<thead>
<tr>
<th>Year</th>
<th>Taiwan</th>
<th>China</th>
<th>Japan</th>
<th>Korea</th>
<th>Total (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>tons</td>
<td>%</td>
<td>tons</td>
<td>%</td>
<td>tons</td>
</tr>
<tr>
<td>2006</td>
<td>31.5</td>
<td>19.7</td>
<td>77</td>
<td>48.1</td>
<td>29</td>
</tr>
<tr>
<td>2007</td>
<td>4</td>
<td>5.8</td>
<td>26</td>
<td>37.9</td>
<td>25.1</td>
</tr>
<tr>
<td>2008</td>
<td>7</td>
<td>13.9</td>
<td>10</td>
<td>19.8</td>
<td>22.5</td>
</tr>
<tr>
<td>2009</td>
<td>19</td>
<td>18.3</td>
<td>28</td>
<td>28.1</td>
<td>29.5</td>
</tr>
<tr>
<td>2010</td>
<td>1</td>
<td>2.4</td>
<td>10.5</td>
<td>25.2</td>
<td>19.5</td>
</tr>
<tr>
<td>2011</td>
<td>0.7</td>
<td>2.0</td>
<td>8</td>
<td>22.9</td>
<td>19.5</td>
</tr>
<tr>
<td>2012*</td>
<td>0.4-0.6</td>
<td>5-6</td>
<td>12-14</td>
<td>2-4</td>
<td>20-25</td>
</tr>
</tbody>
</table>

* : Prediction

**Taiwan is facing the eel aquaculture collapse in the recent 3 years because of the shortage of glass eel!!**
Change of glass eel price in Taiwan

This year
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鰻魚 (*Anguilla* spp) in Taiwan

<table>
<thead>
<tr>
<th>Species</th>
<th>D. Fin</th>
<th>Dist.</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>A. japonica</em></td>
<td>Long</td>
<td>Temperate</td>
<td>Uniform</td>
</tr>
<tr>
<td><em>A. marmorata</em></td>
<td>Long</td>
<td>Tropical</td>
<td>Marble</td>
</tr>
<tr>
<td><em>A. celebesensis</em></td>
<td>Long</td>
<td>Tropical</td>
<td>Marble</td>
</tr>
<tr>
<td><em>A. bicolor pacific</em></td>
<td>Short</td>
<td>Tropical</td>
<td>Uniform</td>
</tr>
</tbody>
</table>

New species (呂宋鰻 *A. luzonensis*, or 黃氏鰻 *A. hungi*)

生活史至今仍然是謎。
Longfinned eel: *A. japonica* and *A. marmorata*; shortfinned eel: *A. bicolor pacifica*
The difference in pigmentation pattern of glass eel among species
Pigmentation stage of glass eel

Glass eel is called 玻璃鰻 in Chinese and シラス(白子)ウナギ in Japanese.

Elver is called 鰻線 in Chinese and クロコ(黒子) in Japanese.

The pigmentation stage is not very clear between glass eel and elver. In general, before VIA2 is glass eel, after VIA3 is elver (Fukuda 2010).
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Species compositions of glass eels from Hsiukulan creek (HKL) of eastern Taiwan, and Tanshui River (TS) and Kao-Ping River (KP) of western Taiwan.
Seasonal and spatial distribution of the glass eel of Japanese eel in Taiwan
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   2.3. The effects of environmental cues and the age of leptocephalus at metamorphosis on upstream migration timing of glass eel
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Ontogenetic change and dispersal process of the Japanese eel from spawning ground to the estuary

- Leptocephalus
- Metamorphosing
- Glass Eel

Map showing the Kuroshio Current, Mindanao Current, Subtropical Countercurrent, North Equatorial Current, and the movement of the Japanese eel from spawning ground to the estuary.

Ontogenetic changes and dispersal processes are illustrated:
- Embryo
- Yolk-sac stage
- Leptocephalus
- Glass eel
- Elver

15 mm

Y C M S T
# Leptocephalus metamorphosis timing and larval dispersal distance

\[ d = \nu \times \triangle t \]

\[ = 96 \text{ km d}^{-1} \times 21 \text{d} \]

\[ = 2016 \text{ km} \]

<table>
<thead>
<tr>
<th>Sampling site</th>
<th>Date</th>
<th>Size</th>
<th>Total length</th>
<th>( T_m )</th>
<th>( T_{r-m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taiwan</td>
<td>30-Dec-92</td>
<td>30 (16)</td>
<td>57.0±2.0</td>
<td>117.7±14.3</td>
<td>39.2±6.8</td>
</tr>
<tr>
<td></td>
<td>T₂</td>
<td>24-Mar-93</td>
<td>30 (14)</td>
<td>56.1±2.4</td>
<td>121.4±12.0</td>
</tr>
<tr>
<td></td>
<td>S₁(North)</td>
<td>30-Dec-92</td>
<td>30 (12)</td>
<td>56.8±2.3</td>
<td>125.9±14.7</td>
</tr>
<tr>
<td></td>
<td>S₂</td>
<td>17-Feb-93</td>
<td>30 (13)</td>
<td>55.9±2.2</td>
<td>115.8±8.1</td>
</tr>
<tr>
<td>China</td>
<td>M</td>
<td>1-Mar-93</td>
<td>30 (20)</td>
<td>55.1±1.9</td>
<td>128.4±6.9</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>17-Feb-93</td>
<td>30 (23)</td>
<td>55.6±1.9</td>
<td>137.9±11.3</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>3-May-93</td>
<td>30 (23)</td>
<td>58.3±1.8</td>
<td>135.5±11.3</td>
</tr>
<tr>
<td>Japan</td>
<td>I</td>
<td>10-Jan-94</td>
<td>30 (10)</td>
<td>57.4±2.3</td>
<td>137.0±12.9</td>
</tr>
</tbody>
</table>
Age of Japanese glass eel at recruitment

Cheng and Tzeng
1996 MEPS 131: 87-96
鰻線漁獲量的日變化與月齢、水溫之關係

Biological rhythm and zetegiber
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All stages of eels in freshwater are heavily exploited.
The exploitation rate of glass eel in Taiwan, 54 to 75%, estimated from each of the recruitment wave in the fishing season 1982-83 (Tzeng 1984)

TABLE 1
The initial population size ($N_0$), catchability ($q$) and rate of exploitation ($E$) estimated from the regression of CPUE on cumulative fishing effort based on catch data of 7 immigrating shoals of elvers

<table>
<thead>
<tr>
<th>Duration</th>
<th>$\Sigma X_t$</th>
<th>$\Sigma C_t$</th>
<th>$r$</th>
<th>$F$-value</th>
<th>Estimated parameter</th>
<th>Rate of exploitation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>days</td>
<td></td>
<td></td>
<td></td>
<td>$N_0$</td>
<td>$q$</td>
</tr>
<tr>
<td>1. Dec. 17-25, 1982</td>
<td>9</td>
<td>209</td>
<td>1,5817</td>
<td>-0.977</td>
<td>148.95**</td>
<td>23,780.9</td>
</tr>
<tr>
<td>2. Jan. 2-5, 1983</td>
<td>4</td>
<td>25</td>
<td>1,632</td>
<td>-0.885</td>
<td>7.196**</td>
<td>1,461.9</td>
</tr>
<tr>
<td>3. Jan. 11-16</td>
<td>6</td>
<td>88</td>
<td>3,516</td>
<td>-0.925</td>
<td>23.635**</td>
<td>7,973.4</td>
</tr>
<tr>
<td>4. Jan. 23-28</td>
<td>6</td>
<td>97</td>
<td>6,607</td>
<td>-0.915</td>
<td>20.519*</td>
<td>12,252.8</td>
</tr>
<tr>
<td>5. Feb. 13-18</td>
<td>6</td>
<td>150</td>
<td>9,118</td>
<td>-0.945</td>
<td>33.260**</td>
<td>16,492.1</td>
</tr>
<tr>
<td>6. Feb. 21-26</td>
<td>6</td>
<td>58</td>
<td>1,890</td>
<td>-0.984</td>
<td>125.213**</td>
<td>2,518.3</td>
</tr>
<tr>
<td>7. Mar. 13-17</td>
<td>5</td>
<td>24</td>
<td>6,91</td>
<td>-0.966</td>
<td>36.325**</td>
<td>916.4</td>
</tr>
</tbody>
</table>

$\Sigma X_t$: cumulative fishing effort in man-night
$\Sigma C_t$: cumulative catch in number of elvers
$r$: correlation coefficient
$F$-value: the probability of significance of regression line is given as
*: 5%, **: 1%, ns: non-significance.
Yield-Per-Recruit model analysis

Growth overfishing is closed

Growth overfishing

Current fishing mortality

Fishing mortality (year\(^{-1}\))
Spawner-per-recruit model:

Recruitment overfishing might have occurred.
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Table 1. Results of regression analyses of $\log_{10}$ (eel catch) against climate indices.

<table>
<thead>
<tr>
<th></th>
<th>Annual</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>$-0.316(1 \text{yr})$</td>
</tr>
<tr>
<td>NEC</td>
<td>$-0.310(3 \text{yr})$</td>
<td>NS</td>
<td>$-0.343(3 \text{yr})$</td>
<td>$-0.282(1 \text{yr})$</td>
<td>NS</td>
</tr>
<tr>
<td>Niño3.4</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Niño0.4</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Niño3</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Niño1.2</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>SOI</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>QBO</td>
<td>$-0.272(3 \text{yr})$</td>
<td>$-0.339(1 \text{yr})$</td>
<td>$0.394(2 \text{yr})$</td>
<td>$-0.287(3 \text{yr})$</td>
<td>$0.286(1 \text{yr})$</td>
</tr>
<tr>
<td>NPGO</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>PDO</td>
<td>$-0.308(1 \text{yr})$</td>
<td>$-0.399(2 \text{yr})$</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>NPI</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>$0.291(1 \text{yr})$</td>
</tr>
<tr>
<td>WPO</td>
<td>$0.289(2 \text{yr})$</td>
<td>NS</td>
<td>NS</td>
<td>$0.472(1 \text{yr})$</td>
<td>$0.417(1 \text{yr})$</td>
</tr>
<tr>
<td>Eddy kinetic energy</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Sunspot</td>
<td>$0.328(0 \text{yr})$</td>
<td>$0.306(0 \text{yr})$</td>
<td>$0.309(0 \text{yr})$</td>
<td>NS</td>
<td>$0.367(0 \text{yr})$</td>
</tr>
</tbody>
</table>

Autocorrelation is accounted for using estimated generalized least squares. Data are normalized to unit mean and variance before analyses. When correlations are significant for multiple lags, all significant correlations are presented. The full table is provided in Supporting Information S1. Only the regression coefficient significant at $p<0.05$ is presented. NS indicates that no significant correlation was found in all lags (0 to 5 years). Parenthesis encloses the years that the climate index leads the eel catches. We investigated the lag up to 5 years. For QBO, correlation beyond 3 years is omitted, considering its biennial nature. doi:10.1371/journal.pone.0030805


Figure 2. Index for latitudinal shift of NEC bifurcation.

http://www.plosone.org/article/info:doi/10.1371/journal.pone.0030805
2) A weak coherence between Eel vs Summer NEC occurs at the time scale of 5 to 7 year, which have not been found in long-term correlation analysis in Table 1.
Fig. 2 Time series change of sunspot and glass eel (elver) catch in Taiwan, 1967-2008.
Fig. 3 Wavelet power spectrum (left) and global power spectrum (right) of log10(eel catch).
The cross wavelet coherence analyses between various climate change indexes and glass eel catch are as follows:

1) A strong positive coherence between Eel vs sunspot occurs at the scale of 10 to 13 years (Fig. 4a)
3) The eel catch in relation to the climate indexes such as NINO3.4 (El Nino near equatorial), NPI (North Pacific Index, a sea level pressure in the region of 30°-65°N, 160°E-145°W, derived from SST), and QBO (Quasi Biannual Oscillation, an east-westward wind field) changed with a 1-3 year high frequency correlation (Figs. 4c-e).
4) On the contrary, the eel catch in relation to WPO (Western Pacific Oscillation, a low altitude (500mb) high pressure center in the eastern Japan) changed with a 9-13 year low frequency correlation (Fig. 4f).
5) Meanwhile, the coherence between summer WPO vs annual sunspots indicated sunspots may lead the change of WPO at the time scale of 9-13 years (Fig.4g).

The wavelet coherence between various climate change indexes and log10(eel catch) indicated that the catch of glass eel was affected by various climate indexes at different time scale.
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Why eel resource decline?

Habitat degradation

Glass eel overfishing

Global climate change
Discussion and conclusion

**Strategy for sustaining the eel aquaculture industry and fisheries**

- To solve the glass eel crisis for the insufficient *A. japonica* glass eel for aquaculture, the development of the aquaculture techniques of exotic eel species (such as *A. marmorata*, *A. bicolor*, *A. mossambica*) is necessary.
- To reduce the catch of the glass eel of *A. japonica* because of over exploitation.
- To stop the yellow eel fishery in the river and to increase the escapement of the silver eel for the recovery of glass eel of *A. japonica*.
- The long-term glass eel catch decline in Taiwan depends on population level itself, similar to the other countries.
- In addition, Taiwan is located in the edge of the distribution of Japanese eel in the western Pacific, that lead to the climate change effect on the catch of glass eel is more sensitive in Taiwan than other counties. The catch of glass eel was highly correlated with various climate transportation might be influenced by the climate changes that are originally governed by the solar activity.
Thank You for Your Attention

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Eel field study in NW Luzon Philippine on Jan 18, 2009 before Chinese Lunar New Year