The role of movement in determining the global distribution of marine biomass

James Watson  (Princeton: jrwatson@princeton.edu)
Charlie Stock, Jorge Sarmiento

Atmospheric and Oceanic Sciences Program
Dept. Ecology and Evolutionary Biology
Geophysical Fluid Dynamics Laboratory (NOAA)
A. Global Fisheries Production

- How much biomass does the ocean produce?
A. Global Fisheries Production

- How much biomass does the ocean produce?

Photosynthesis and Fish Production in the Sea

The production of organic matter and its conversion to higher forms of life vary throughout the world ocean.

John H. Ryther

Science, 1969; Pauly & Christensen 1995, Chassot et al. 2010
A. Global Fisheries Production

- How much biomass does the ocean produce?

**Photosynthesis and Fish Production in the Sea**

The production of organic matter and its conversion to higher forms of life vary throughout the world ocean.

John H. Ryther

Science, 1969; Pauly & Christensen 1995, Chassot et al. 2010

Phytoplankton

Trophic transfer efficiency
A. Global Fisheries Production

- How much biomass does the ocean produce?

**Photosynthesis and Fish Production in the Sea**

The production of organic matter and its conversion to higher forms of life vary throughout the world ocean.

John H. Ryther

Science, 1969; Pauly & Christensen 1995, Chassot et al. 2010

---

**Trophic transfer efficiency**

Phytoplankton → Zooplankton

10%
A. Global Fisheries Production

- How much biomass does the ocean produce?

Photosynthesis and Fish Production in the Sea

The production of organic matter and its conversion to higher forms of life vary throughout the world ocean.

John H. Ryther

Science, 1969; Pauly & Christensen 1995, Chassot et al. 2010

Phytoplankton 10% Zooplankton 10% Small Fish

Trophic transfer efficiency
A. Global Fisheries Production

- How much biomass does the ocean produce?

**Photosynthesis and Fish Production in the Sea**

The production of organic matter and its conversion to higher forms of life vary throughout the world ocean.

John H. Ryther

Science, 1969; Pauly & Christensen 1995, Chassot et al. 2010

---

Phytoplankton **→** Zooplankton **→** Small Fish **→** Big Fish

**Trophic transfer efficiency**
A. Global Fisheries Production

- How much biomass does the ocean produce?

**Photosynthesis and Fish Production in the Sea**

The production of organic matter and its conversion to higher forms of life vary throughout the world ocean.

John H. Ryther

Science, 1969; Pauly & Christensen 1995, Chassot et al. 2010

<table>
<thead>
<tr>
<th>Province</th>
<th>Primary production [tons (organic carbon)]</th>
<th>Trophic levels</th>
<th>Efficiency (%)</th>
<th>Fish production [tons (fresh wt.)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceanic</td>
<td>(16.3 \times 10^9)</td>
<td>5</td>
<td>10</td>
<td>(16 \times 10^3)</td>
</tr>
<tr>
<td>Coastal</td>
<td>(3.6 \times 10^9)</td>
<td>3</td>
<td>15</td>
<td>(12 \times 10^3)</td>
</tr>
<tr>
<td>Upwelling</td>
<td>(0.1 \times 10^9)</td>
<td>1½</td>
<td>20</td>
<td>(12 \times 10^3)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td>(24 \times 10^3)</td>
</tr>
</tbody>
</table>

**Trophic transfer efficiency**

Phytoplankton – 10% → Zooplankton – 10% → Small Fish – 10% → Big Fish – 10%
A. Global Fisheries Production

- How much biomass does the ocean produce?

### Photosynthesis and Fish Production in the Sea

The production of organic matter and its conversion to higher forms of life vary throughout the world ocean.

John H. Ryther

Science, 1969; Pauly & Christensen 1995, Chassot et al. 2010

<table>
<thead>
<tr>
<th>Province</th>
<th>Primary production [tons (organic carbon)]</th>
<th>Trophic levels</th>
<th>Efficiency (%)</th>
<th>Fish production [tons (fresh wt.)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceanic</td>
<td>16.3 $\times 10^9$</td>
<td>5</td>
<td>10</td>
<td>16 $\times 10^3$</td>
</tr>
<tr>
<td>Coastal</td>
<td>3.6 $\times 10^9$</td>
<td>3</td>
<td>15</td>
<td>12 $\times 10^3$</td>
</tr>
<tr>
<td>Upwelling</td>
<td>0.1 $\times 10^9$</td>
<td>1½</td>
<td>20</td>
<td>12 $\times 10^3$</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>24 $\times 10^3$</td>
</tr>
</tbody>
</table>

Photic transfer efficiency

- Phytoplankton 10%
- Zooplankton 10%
- Small Fish 10%
- Big Fish 10%
A. Global Fisheries Production

How much biomass does the ocean produce?

Photosynthesis and Fish Production in the Sea

The production of organic matter and its conversion to higher forms of life vary throughout the world ocean.

John H. Ryther

Science, 1969; Pauly & Christensen 1995, Chassot et al. 2010

Table 3. Estimated fish production in the three ocean provinces defined in Table 2.

<table>
<thead>
<tr>
<th>Province</th>
<th>Primary production [tons (organic carbon)]</th>
<th>Trophic levels</th>
<th>Efficiency (%)</th>
<th>Fish production [tons (fresh wt.)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceanic</td>
<td>$16.3 \times 10^9$</td>
<td>5</td>
<td>10</td>
<td>$16 \times 10^9$</td>
</tr>
<tr>
<td>Coastal</td>
<td>$3.6 \times 10^9$</td>
<td>3</td>
<td>15</td>
<td>$12 \times 10^7$</td>
</tr>
<tr>
<td>Upwelling</td>
<td>$0.1 \times 10^9$</td>
<td>1½</td>
<td>20</td>
<td>$12 \times 10^7$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>24 \times 10^7</strong></td>
</tr>
</tbody>
</table>

Maximum fisheries production: 240 MT year$^{-1}$

Trophic transfer efficiency
Can we do better than the trophic transfer efficiency (nonlinear relationships, spatial resolution)?
Global Ecosystem Modeling

- Can we do better than the trophic transfer efficiency (nonlinear relationships, spatial resolution)?

Figs: Charles Stock: COBALT

Charles A Stock, John P Dunne, and Jasmin G John. Progress In Oceanography, In press
Global Ecosystem Modeling

- Can we do better than the trophic transfer efficiency (nonlinear relationships, spatial resolution)?

![Map showing large primary production](#)

**COBALT**
Carbon, Ocean Biogeochemistry and Lower Trophys
Charles Stock, John Dunne, Jasmin John; GFDL

Mortality to higher predators

Figs: Charles Stock: COBALT

Charles A Stock, John P Dunne, and Jasmin G John. Progress In Oceanography, In press
The challenge...

Quantify upper-trophic, or fisheries, production at a global scale...

- Like plankton, big things are highly diverse
- Unlike plankton, big things move against currents
Size-based Models

A conserved feature of marine systems around the globe:

![Graph showing size-based models for different marine ecosystems](Image)

Big, medium, small... size simplifies

Many things scale with size
- e.g. swimming speed, metabolic rates and predator-prey relationships
- Metabolic Theory of Ecology (Jim Brown @ U. New Mexico)

Barnes et al. 2009
A Size-based Model: formulation

Model the rate of change of biomass of a particular size-class:

\[
\frac{d B_i}{d t} = \ldots
\]

i = medium fish
A Size-based Model: formulation

Model the rate of change of biomass of a particular size-class:

\[
\frac{dB_i}{dt} = \text{Eat}(j)
\]
A Size-based Model: formulation

Model the rate of change of biomass of a particular size-class:

\[
\frac{dB_i}{dt} = \text{Eat}(j) - \text{Get eaten}(k)
\]

Images not to scale
A Size-based Model: formulation

Model the rate of change of biomass of a particular size-class:

\[
\frac{d B_i}{dt} = \text{Eat}(j) - \text{Get eaten}(k) - \text{Metabolize}(i) + \text{move}(i)
\]

Images not to scale
A Size-based Model: formulation

Model the rate of change of biomass of a particular size-class:

\[
\frac{dB_i}{dt} = \text{Eat}(j) - \text{Get eaten}(k) - \text{Metabolize}(i) + \text{move}(i)
\]

Type II feeding function (PPMR, volume searched)

Allometric power law ... as$_i^b$

Gradient ascent

\[ J = f(dB_j/dx) \]

Images not to scale
A Size-based Model: results

Charles A Stock, John P Dunne, and Jasmin G John. Progress In Oceanography, In press
A Size-based Model: results
A Size-based Model: results
A Size-based Model: results
A Size-based Model: results

Size-based model estimates biomass size spectra...
A Size-based Model: results

Size-based model estimates biomass size spectra...
A Size-based Model: results

Forage fish

~100g

Top predator

>1kg
A Size-based Model: results

Forage fish

~100g

>1kg

Top predator
A Size-based Model: results

Forage fish

~100g

No movement

>1kg

Top predator
A Size-based Model: results

Forage fish

With net-growth following movement

c) FF move

d) TP move
A Size-based Model: results

Ecoregions with net-growth following movement
Limitations
Limitations

Lacks species specific details:
- Tuna in the Indian ocean
- No complex migration, no “extreme” parameters
Limitations

Lacks species specific details:
- Tuna in the Indian ocean
- No complex migration, no “extreme” parameters

No big fish!

Top predator
Limitations

Lack species specific details
- It can’t resolve sardine and anchovy (only “forage fish”)

![Graph showing the relationship between HUMBOLDT CURRENT and El Niño index over time. The graph includes data points for surplus production (z-score) from 1975 to 2005.]
Limitations

Highly sensitive to parameters

Global ocean biomass (tonnes): ~ 86.2x10^9 (x30 Jennings et al. 2009)
Biomass production (gm^-2 yr^-1): ~ 0.5x10^{10} (x0.5 Jennings et al. 2009)

Can completely change these results with a different consumption efficiency (0.7 to 0.5)
Limitations

Highly sensitive to parameters

Global ocean biomass (tonnes): $\sim 86.2 \times 10^9$ (x30 Jennings et al. 2009)
Biomass production (gm$^{-2}$yr$^{-1}$): $\sim 0.5 \times 10^{10}$ (x0.5 Jennings et al. 2009)

Can completely change these results with a different consumption efficiency (0.7 to 0.5)

Empirical gut content analysis

Barnes et al. 2009
Limitations

Highly sensitive to parameters

Global ocean biomass (tonnes): $\sim 86.2 \times 10^9$ (x30 Jennings et al. 2009)
Biomass production (g m$^{-2}$ yr$^{-1}$): $\sim 0.5 \times 10^{10}$ (x0.5 Jennings et al. 2009)

Can completely change these results with a different consumption efficiency (0.7 to 0.5)

Empirical gut content analysis

Barnes et al. 2009
Comparison

No ontogeny (not “size-structured”),
- poor estimates of recruitment

Size-based population model
Comparison

No ontogeny (not “size-structured”),
- poor estimates of recruitment
Comparison

No ontogeny (not “size-structured”),
- poor estimates of recruitment

Size-based population model
Comparison

No ontogeny (not “size-structured”),
- poor estimates of recruitment

Size-based population model
Comparison

No ontogeny (not “size-structured”),
- poor estimates of recruitment
Comparison

No ontogeny (not “size-structured”),
- poor estimates of recruitment
Comparison

No ontogeny (not “size-structured”),
- poor estimates of recruitment

Size-based population model

Size-structured model
Comparison

No ontogeny (not “size-structured”),
- poor estimates of recruitment
Comparison

No ontogeny (not “size-structured”),
- poor estimates of recruitment

Size-based population model

Size-structured model
Size based models:
- ecological understanding: yes, movement is important
- prediction? useful given the conditions
Jorge Sarmiento (Princeton)
Simon Levin (Princeton)
Charlie Stock (NOAA / GFDL)

Emma Fuller (Princeton)
Andrew Tilman (Princeton)
Malin Pinsky (Rutgers)

... and many others
Thank you

Jorge Sarmiento (Princeton)
Simon Levin (Princeton)
Charlie Stock (NOAA / GFDL)

Emma Fuller (Princeton)
Andrew Tilman (Princeton)
Malin Pinsky (Rutgers)

... and many others

James Watson
jrwatson@princeton.edu