# Challenges in Marine Statistical Ecology

## From Sea Cucumbers to Grey Seals

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*Statistics is driven by practical application*


# What is Marine Ecology?

*Marine ecology is concerned with organisms that live in or near the ocean, their behaviors, and their interactions with the environment.*

# Scientific Questions

*For example...*

- Can we understand the processes affecting the abundance of fish populations?
- Are invertebrate species being increasingly exploited?
- Are Grey Seals responsible for depleted Atlantic Cod stocks on the Eastern Scotian Shelf?

# Scientific Answers

Require experiments, field surveys and **statistical modeling**.

Computer intensive with respect to the:

1. amount of data (explosive increase)
2. methodologies

# Fish Population Dynamics

| | |
|---|---|
| Central Idea | Understanding fish population dynamics |
| Data | Comprehensive database of stock assessments |
| Methods | Multivariate state space models |

www.marinebiodiversity.ca/RAMlegacy/srdb/updated-srdb

# Background

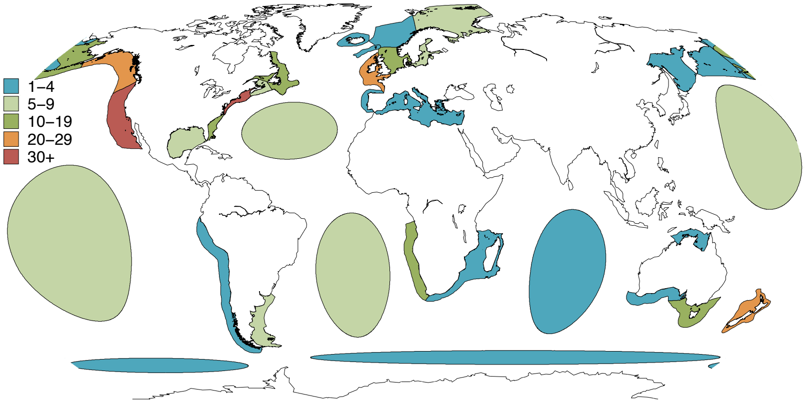
**Stock**: A subpopulation of a particular species of fish, for which intrinsic parameters (growth, recruitment, mortality and fishing mortality) are the only significant factors in determining population dynamics, while extrinsic factors (immigration and emigration) are considered to be insignificant.

**Recruitment**: The process whereby new fish enter the portion of the population vulnerable to fishing from earlier life history stages. Also used for the number of recruits in a given year.

*The concept that fish populations could be regulated by virtue of their abundance at an early age was taken up by Ricker (1954).*

# RAM Legacy Stock Recruitment Database

- A methodological testbed for novel statistical methods
- Approximately 640 stocks
- Records going back to early 1900s



# Traditional Approach

$$R_t = \alpha S_{t-\tau} e^{\beta S_{t-\tau}}$$

- $R_t$ is the abundance of fish of a given (young) age at time $t$
- $\tau$ age at recruitment in years
- $\alpha$ is the slope at the origin of relationship
- $S_{t-\tau}$ is the spawner abundance when the recruits of age $\tau$ were spawned
- $\beta$ is the density-dependent mortality rate

*This is the form regularly fit to recruitment data for the purpose of forecasting recruitment in coming years*

# Maximum Reproductive Rate

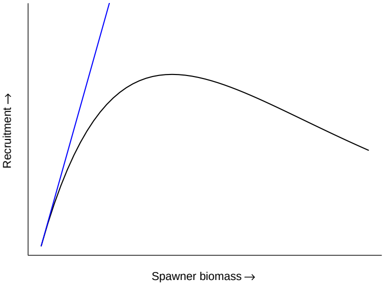
**Maximum Reproductive Rate** $\alpha$:

- Parameter of central importance to population ecology and resource management
- Maximum number of recruits produced per spawner at low population density (in the absence of density-dependent mortality)
- Determines the intrinsic rate of population growth, productivity, overfishing limits.

# Motivation

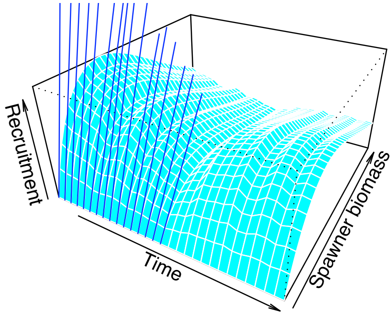
- Traditional approach to recruitment doesn't allow for **inter**-annual variation in $\alpha$.
- Allowing for such stochastic variation provides an opportunity to track changes in productivity.
- Huge array of hypothesized drivers of productivity:
    - Physical environment
        - temperature
        - salinity
    - Biological environment
        - species interactions
        - food availability
    - Life history characteristics
        - maternal effects
- First we must answer the question of "*how* has productivity changed?"

# Traditional Approach




$$R_t = \alpha S_{t-\tau} e^{\beta S_{t-\tau}}$$

# Time-Varying Approach




$$R_t = \alpha_t S_{t-\tau} e^{\beta S_{t-\tau}}$$

# State Space Model Formulation

- Linearized Ricker model:

$$ln(R_t/S_{t-\tau}) = a_t + \beta S_{t-\tau}$$

- Assume a random walk on $a_t$
- Formulate as a state space model:

$$\begin{aligned} y_t &= F_t(\theta_t) + v_t, \quad v_t \sim N(0, V_t) \\ \theta_t &= G_t(\theta_{t-1}) + w_t, \quad w_t \sim N(0, W_t) \end{aligned}$$

where

$$y_t = ln(R_t/S_{t-\tau}), \quad \theta_t = \begin{pmatrix} a_t \\ \beta \end{pmatrix}, \quad F_t = (1 \quad S_{t-\tau})$$

$$G_t = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad V_t = (\sigma_v^2), \quad W_t = \begin{pmatrix} \sigma_a^2 & 0 \\ 0 & 0 \end{pmatrix}$$

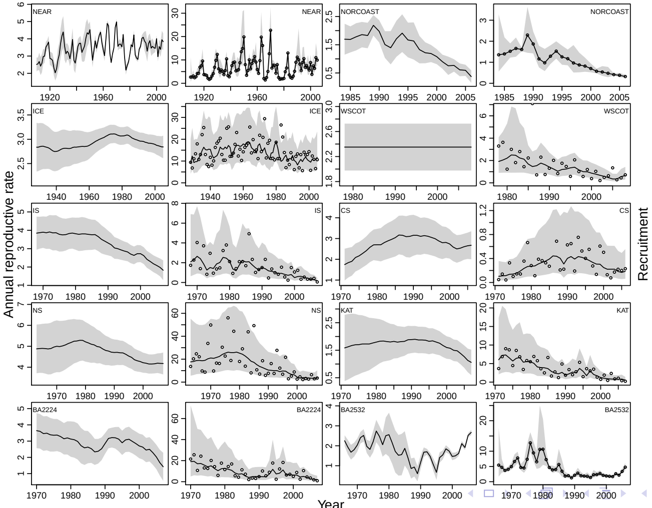
# Details

- State and parameter estimation via kalman filter and smoother
- Alternative formulations for $a_t$ and Ricker relationship
- AIC used to compare models
- Multi-stock formulation
    1. separate measurement error variances for each stock
    2. unstructured covariance matrix

# Application

## 10 Northeast Atlantic Cod stocks

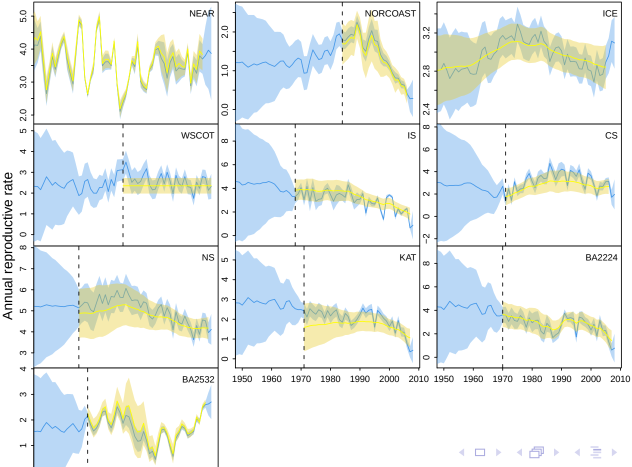
Estimated annual reproductive rates and recruitment



# Multi-stock Formulation

## How similarly are the stocks behaving?

Estimated annual reproductive rates and 95% confidence intervals from univariate (yellow) and multivariate (blue) fits.



# Summary

- Productivity has varied markedly over the time-period investigated
- Many stocks currently at historically low productivity
- Trends largely conserved across regions
- Useful framework that integrates across many dimensions of environmental change affecting recruitment dynamics


$438.
LB.

# Trends in Invertebrate Fisheries

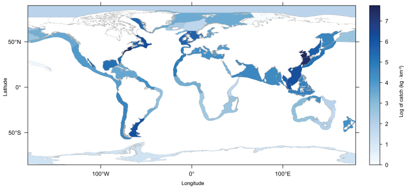
Central Idea: Global evaluation of the trends, drivers, and population and ecosystem consequences of invertebrate fisheries

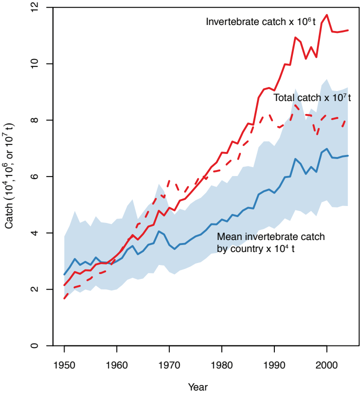
Data: Sea Around Us Project's global catch database and taxa-specific reviews

Methods: GLMs, GAMs etc.

http://www.seaaroundus.org

# The Global Expansion of Invertebrate Fisheries



# Sea Cucumbers

- Increasingly harvested group
- Occur in most benthic marine habitats worldwide
- Help maintain a healthy ocean
- Great social & economic importance
- Highly valuable (sometimes \$400-\$800 per lb)

# Global status of Sea Cucumbers

Challenging to determine:

- General lack of abundance data
- Import and export statistics incomplete
- Trade of sea cucumbers complex

# Goals

1. Synthesize the current status of trends of sea cucumbers worldwide (looking for general pattern(s) of increase and decline)
2. Analyse underlying drivers

*Under an ideal fisheries management scenario, a fishery would develop as a gradual increase towards a plateau near a sustainable yield.*

# Determination of Typical Trajectory

1. Standardized catch
2. Catches lagged so each country's catch reached a maximum in the same year
3. Peak years identified from loess-smoothed curves
4. Exclusions
5. GAM (Hastie and Tibshirani, 1990)

# Model

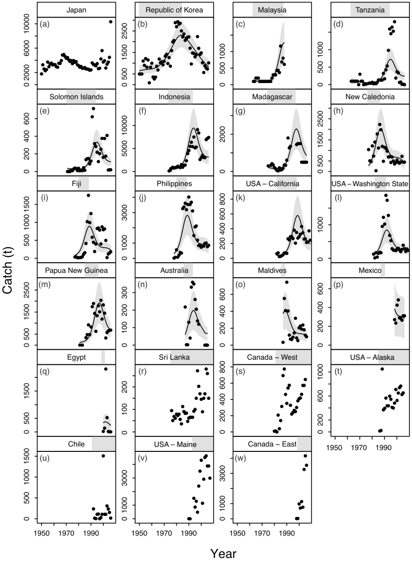
Catch for each year $i$ and country $j$ modelled as follows:

$$\text{Standardized catch}_{ij} \sim gamma(\mu_{ij})$$
$$log(\mu_{ij}) = \beta_j + f(Y_{ij} - Y_{peak_j}) + e_i$$

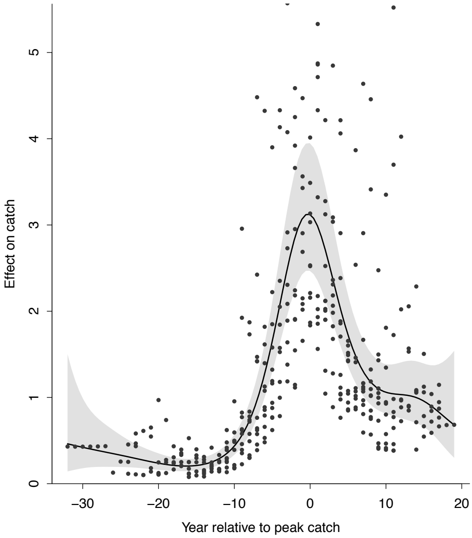
where $\mu_{ij}$ represents the mean of the gamma distribution and $e_i$ represents the autoregressive function:

$$e_i = \phi e_{i-1} + \epsilon_i$$

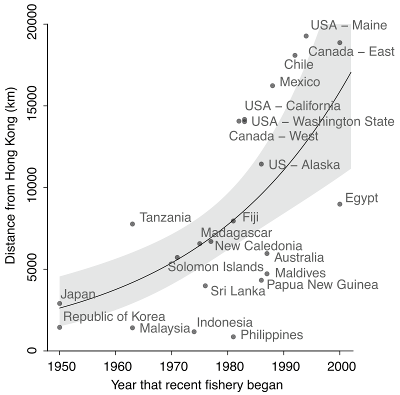
# Catch Trends by Country

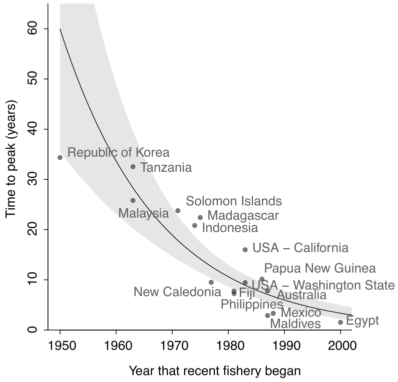


# Global Trajectory



# Drivers


Distance from Hong Kong (km)
Year that recent fishery began
USA – Maine
Canada – East
Chile
Mexico
USA – California
USA – Washington State
Canada – West
US – Alaska
Egypt
Tanzania
Fiji
Madagascar
New Caledonia
Australia
Solomon Islands
Maldives
Papua New Guinea
Sri Lanka
Japan
Republic of Korea
Malaysia
Indonesia
Philippines


Time to peak (years)
Year that recent fishery began
Republic of Korea
Tanzania
Solomon Islands
Malaysia
Madagascar
Indonesia
USA – California
Papua New Guinea
USA – Washington State
New Caledonia
Fiji
Australia
Philippines
Mexico
Maldives
Egypt

# Summary

- In only a few decades, most sea cucumber fisheries around the world have experienced a boom-and-bust pattern.
- Over time this happened faster and further away from the main market in Hong Kong and China.
- $\sim$ 80% of sea cucumber fisheries have experienced population declines.

# More generally...

- New methodologies to quantify spatial and temporal trends in resource status and fishery development
- Since 1950, global invertebrate catches have increased 6-fold
- New fisheries have developed increasingly rapidly

# The Ocean Tracking Network

- An $170-million conservation project headquartered at Dalhousie
- Comprehensive examination of marine life and ocean conditions with emphasis on understanding how they are changing as the earth warms
- Global network of biologists, computer scientists, oceanographers and **statisticians**

http://www.oceantrackingnetwork.org

# OTN Design Principles

| | |
|---|---|
| Central Idea | Estimate distribution of encounters |
| Data | A **new** data type... |
| Methods | Spatial point process analysis |

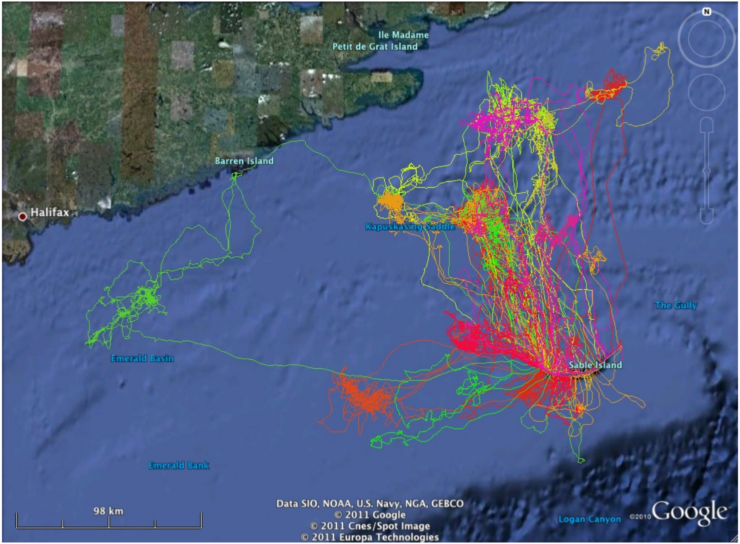
# What is a bioprobe?

- An animal instrumented with a tag
- business card tag
- records instances of proximity to other acoustically tagged animals: **encounters**
- delivers a dataset comprising the times and locations of the encounters

# Application

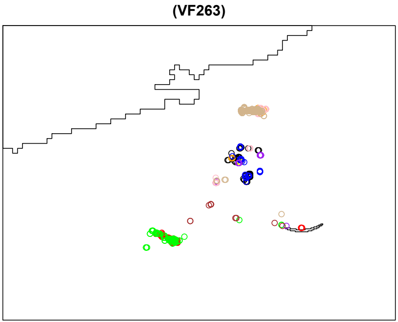
- Grey seals as bioprobes
- Atlantic Cod and other fish *will* have acoustic transmitters embedded
- For now: Seal-Seal encounters and simulated data

# Tracking Data



# Encounter Data

- colors represent seals
- clustered on banks



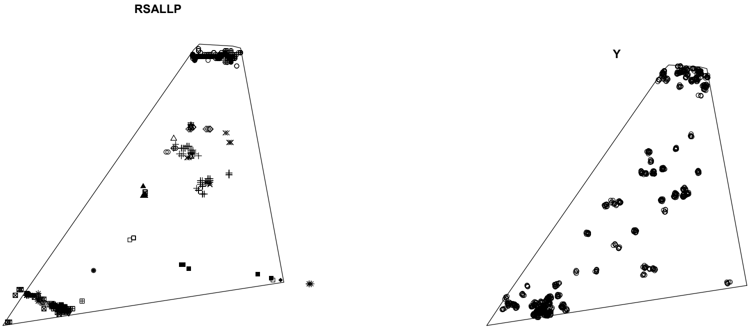
# Spatial Point Process Analysis

- Define a window (space on which process occurs)
  - defines geographic area of interest
  - functions as a boundary for the process
- Describe intensity
  - expected number of points per unit area
  - if constant then a homogeneous Poisson process
  - otherwise changes over the window and an inhomogeneous Poisson process
- Examine Interaction between points
  - pairwise distance methods
  - clustered ?
  - may lead to definition of *parents* and *offspring*

# Seal-Seal Encounters

- Spatial window estimated using the method of Ripley and Rasson (1977, Journal of Applied Probablity)
- Matern cluster process (Waagpetersen, 2004)
  - initial encounters (parents) an inhomogeneous Poisson process
  - each initial encounter has Poisson($\mu$) number of offspring, independently and uniformly distributed in a disc of radius $r$ centered about the parent

# Comparison of Data and Realization



# Moving Forward

- Process describes our data very well
- Doesn't look like they are travelling in pairs or groups
- Allow intensity of the process to depend on the bathymetry (or anything else)
- Seal-Cod encounters
- Does the cod distribution influence the seal distribution?

# Summary

1. A lot more needs to be learned about business card tag performance
2. Work with Oceanography to explore the role of biophysical processes
3. Export bioprobe technology to other projects
4. Visualization tools

# Messages

1. Data and methodology drives science
2. Datasets are expanding... yet getting it and organizing it is a momentous task
3. Active collaboration is essential
4. Statistical methods tested, enhanced...
5. Challenging and exciting!

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DALHOUSIE UNIVERSITY Inspiring Minds

OCEAN TRACKING NETWORK Headquartered at Dalhousie University, Canada

NSERC CRSNG

Thank you.