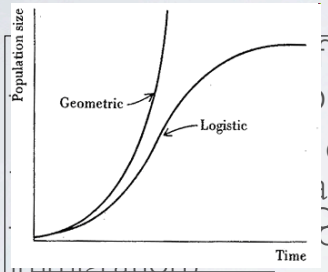
UNDERSTANDING MOVEMENT DATA AND MOVEMENT PROCESSES: WHAT'S THE STATE OF THE ART?

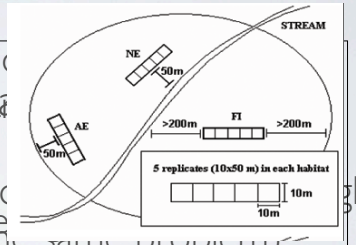
Rob Schick

Jim Clark, Pat Halpin, Scott Loarie, Fernando Colchero, Andy Read, Ben Best, Jason Roberts, Andre Boustany, Dalia Conde, Lucas Joppa, Catherine McClellan, Caroline Good, Chris Slay, Scott Kraus, Bruce Mate, and Mark Baumgartner

WHY STUDY MOVEMENT?

- f interest for a po
- ndance in spa
- density of organ
- of:
- nd time are stud
- d Movement (e
- diff. aspects of the same problem)





Temporal Fluctuations in abundance ⟷ Distribution in space

Animal Ecology — Plant Ecology

Turchin, 1998

POPULATION ECOLOGISTS & DIFFUSION MODELS

$$\frac{\partial N}{\partial t} = f(N) + D\left[\frac{\partial^2 N}{\partial x^2} + \frac{\partial^2 N}{\partial y^2}\right]$$

- From this simple equation we have learned a lot about:
  - Spread of alleles (Fisher 1937)
  - Population Spread (Skellam 1951)
  - Critical patch size (Kierstead & Slobodkin, 1953)
  - Invasives, grouping, seed dispersal, movements in home ranges, spatial predator-prey dynamics (e.g. Okubo, 1980; Okubo & Levin 2002)
  - Population spread through hetergeneous environments (esp. P. Kareiva's dissertation; Kareiva 1990; Turchin 1991, 1998)

DIFFUSION, MOVEMENT, AND RW

- In classical diffusion, one assumes that molecules (or animals) move randomly. Three key themes that are still important in non-diffusion studies:
- Correlated Random Walks
  - Kareiva & Shigesada, 1984
- Area-Restricted Search
  - Kareiva & Odell, 1987
- Spatially varying parameters: From the individual to the population
  - Patlak 1953, Turchin 1991

WHAT CAN WE LEARN FROM STUDYING MOVEMENT?

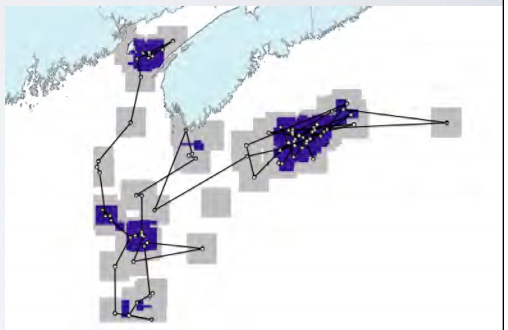
- Search Behavior
- Disease Outbreaks
- (Spatial) Population Dynamics
- Viability of Endangered Species
- Density Dependent Habitat Selection
- Ecosystem Management
- Dispersal Strategies at the Evolutionary Scale

Bowler & Benton, (2005), Biological Reviews 80:205-225

HOW DO YOU STUDY IT?

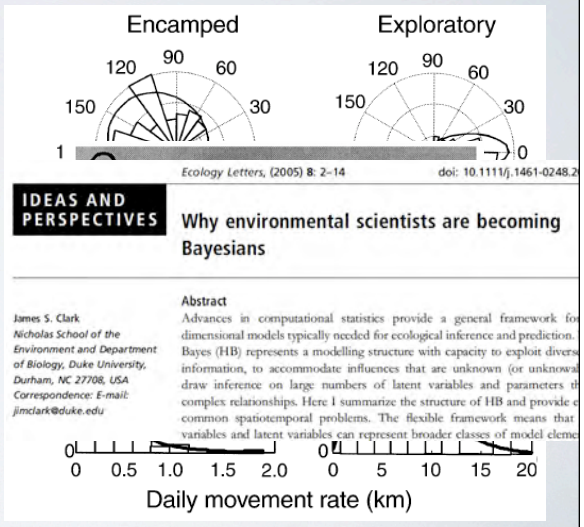
ORIGINS OF THIS TALK

- Started in 2000 when I went to NEAq
- Used kernel densities, mantel tests, and CARTs
- Reviewers didn't like this
- With Steve Lindley implemented an SSM (2004)
- Reviewers didn't like this either…



ANALYTICAL DEVELOPMENTS

- Jonsen et al., 2003, Ecology
- Morales et al., 2004, Ecology
- Clark, 2005, Ecology Letters



Ecology Letters, (2005) 8: 2–14 doi: 10.1111/j.1461-0248.2

IDEAS AND PERSPECTIVES

Why environmental scientists are becoming Bayesians

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Abstract

Advances in computational statistics provide a general framework for dimensional models typically needed for ecological inference and prediction. Bayes (HB) represents a modelling structure with capacity to exploit diverse information, to accommodate influences that are unknown (or unknowa draw inference on large numbers of latent variables and parameters th complex relationships. Here I summarize the structure of HB and provide e common spatiotemporal problems. The flexible framework means that variables and latent variables can represent broader classes of model eleme

ORIGINS, CONTINUED

- Went to see Jim Clark
  - (Fumbled around for a while)
- Went to see Jim *again* (repeat many times):
  - What does this tell you that looking at the map doesn't?
  - Focus on the movement process.
- In the process of developing a new movement model, a group of us at Duke reviewed many of the models currently in use

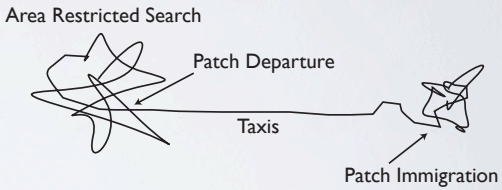
WHAT'S THE STATE OF THE ART?

- Non-inferential movement models
- Inferential movement models
  - Behavior
  - Organism-environment interaction
  - Separating process from observation
- Our new model

Schick et al., (2008), Ecology Letters 11:1138-1150

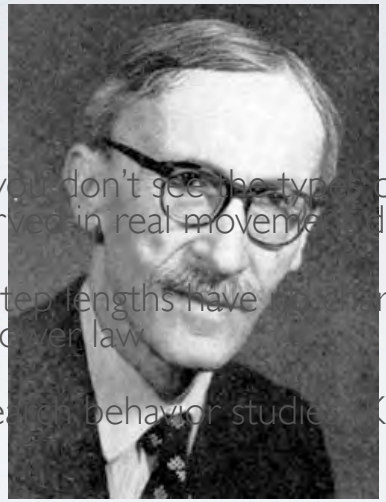
NON-INFERENTIAL MODELS

- Diffusion Models
- Correlated Random Walks
- Lévy Flights
- Multi-behavioral Analysis
- Fractal Analysis
- First Passage Time



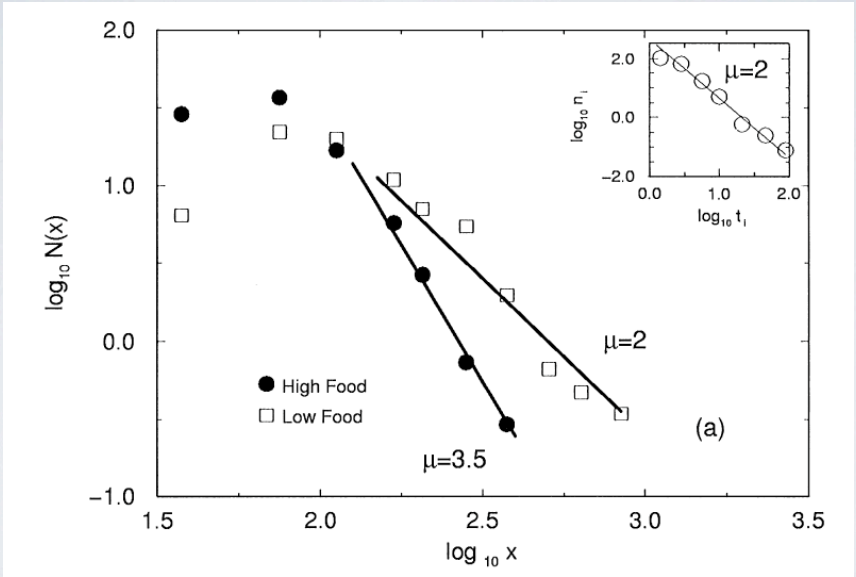
WHAT ARE LÉVY FLIGHTS?

- Typically in a RW you don't see the type of long distance moves often observed in real movement data
- With a Levy RW, step lengths have a characteristic scale and typically follow a power law
- Typically used in search behavior studies (Kareiva & Odell 1987)



Paul Pierre Lévy

LÉVY FLIGHTS



Viswananthan et al. (2000) Physica A

LEVY FLIGHTS - CRITIQUE

- Most importantly, there's no indication of what process gives rise to the observed behavior
- This debate has already played out in the seed dispersal literature
  - Power laws provide "...no understanding of the underlying mechanism." (Okubo & Levin, 1989, Ecology)

LEVY FLIGHTS DISCREDITED

nature Vol 449|25 October 2007|doi:10.1038/nature06199

LETTE

Revisiting
albatross

ndering

Andrew M. Edwards
Vsevolod Afanasyev
& Gandhimohan M.

ene J. Murphy[1],
y[2]

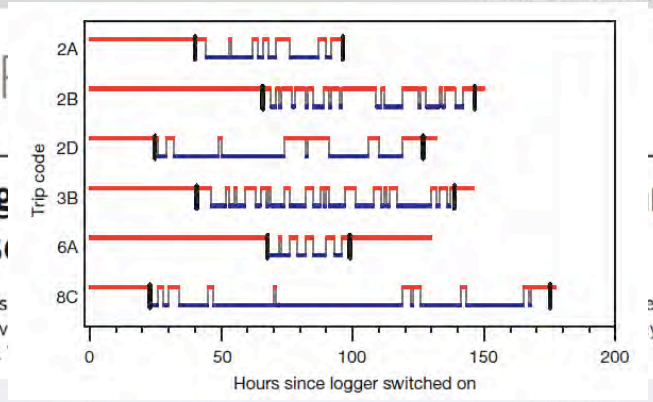
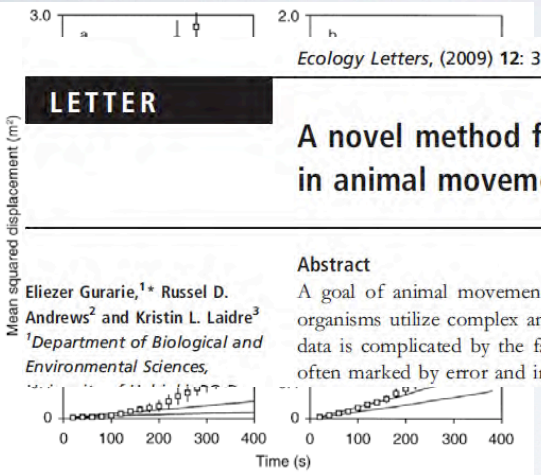


Fig. 1. We conclude that, when time spent by the birds on the nests is accounted for, the original 1992 albatross data do not support Lévy flight behaviour.

INFERENTIAL MODELS: 1) BEHAVIOR

Morales & Ellner (2002), Ecology 83:2240-2247

Morales et al., (2004), Ecology 85:2436-2445



Ecology Letters, (2009) **12**: 395–408 doi: 10.1111/j.1461-0248.2009.01293.x

LETTER

A novel method for identifying behavioural changes in animal movement data

Eliezer Gurarie,[1]* Russel D. Andrews[2] and Kristin L. Laidre[3]
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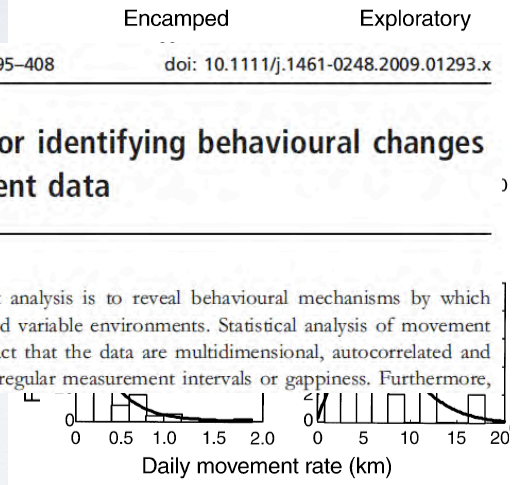
Abstract

A goal of animal movement analysis is to reveal behavioural mechanisms by which organisms utilize complex and variable environments. Statistical analysis of movement data is complicated by the fact that the data are multidimensional, autocorrelated and often marked by error and irregular measurement intervals or gappiness. Furthermore,



INFERENTIAL MODELS: 2) ORG-ENV INTERACTION

- How do animals respond to the environment?
- Do they move differently in different habitats?
- How do they sense changes in habitat?
- In marine settings, how are they influenced by currents?
- In marine settings, what about dynamic covariates in 4D?

TURCHIN, 1991

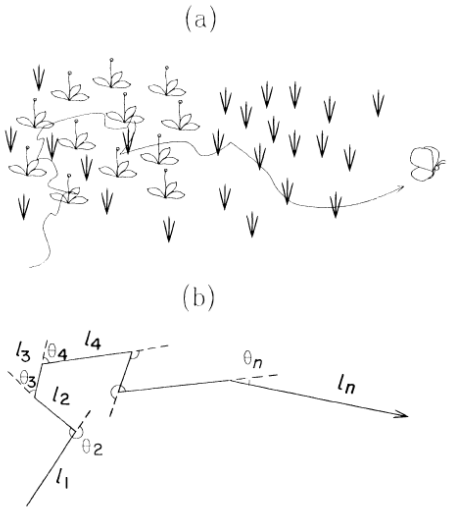


FIG. 1. Movement represented as correlated random walk (CRW). (a) The actual path traced by the organism. (b) The discretized representation of the path.

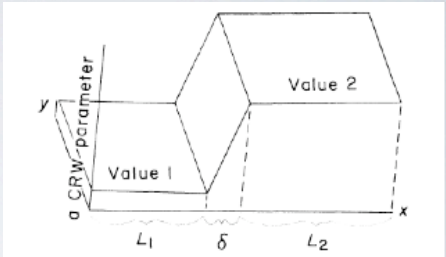
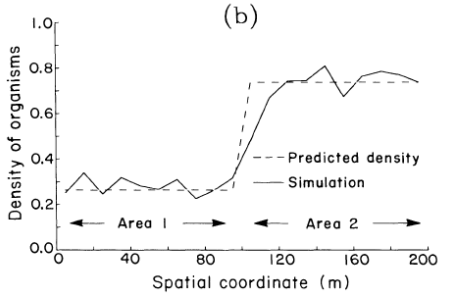
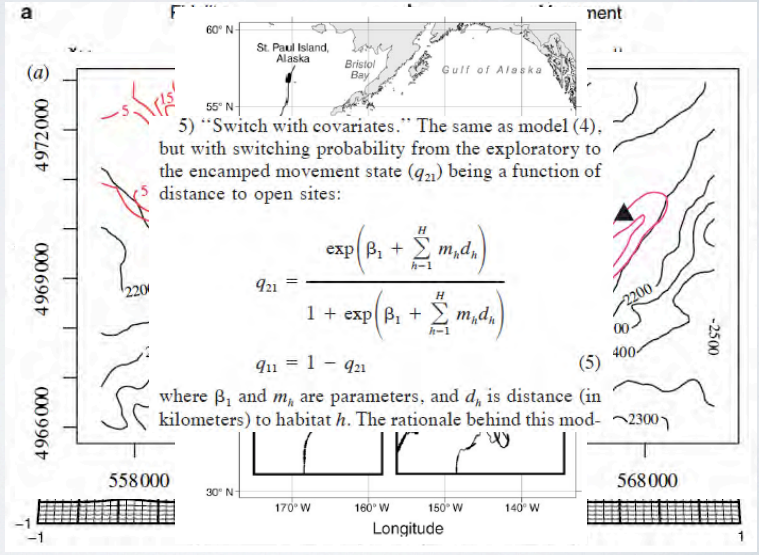


FIG. 2. Spatial variation in a correlated random walk (CRW) parameter. CRW parameters (definitions in Table 1) vary along the spatial coordinate x. Parameters assume constant values within each of the two patches, and change linearly in the transition region between the patches.



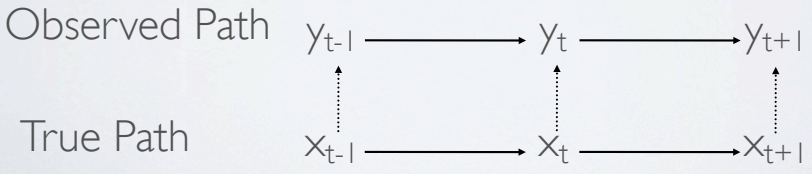
INFERENTIAL MODELS: 2) ORG-ENV INTERACTION

- Morales et al. 2004
- Moorcroft et al., 2006
- Johnson et al., 2008
- Christ et al., 2008

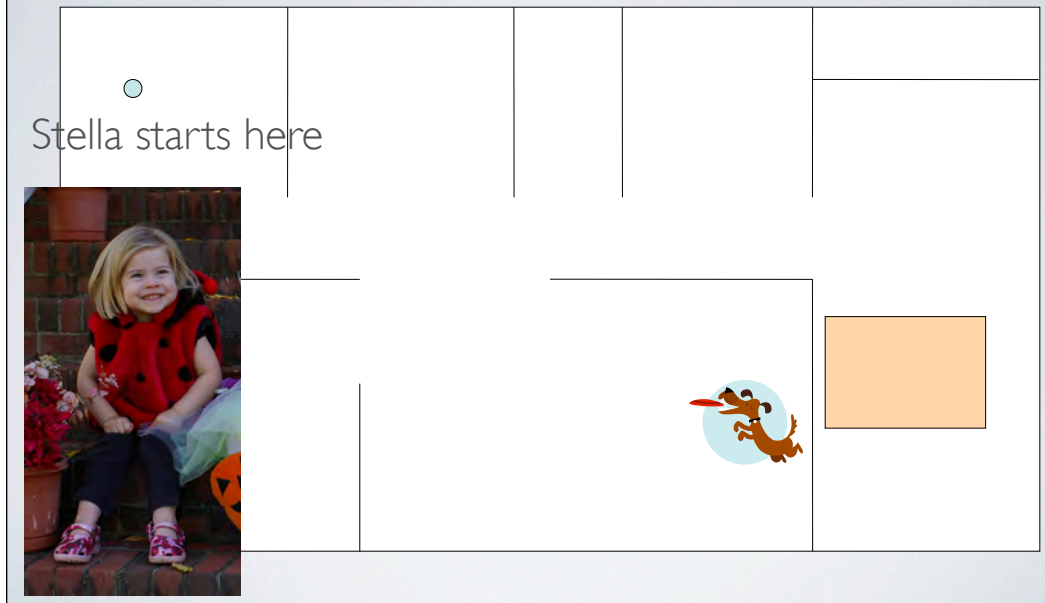


INFERENTIAL MODELS: 3) PROCESS BASED INFERENCE

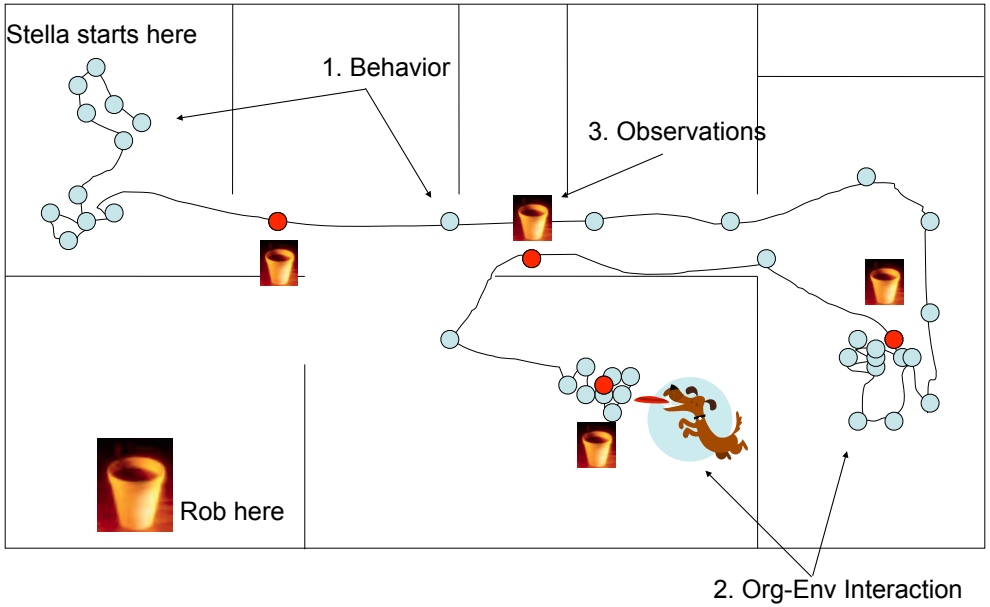
- Inference in the face of incomplete data observed with error
- What are state-space models?
- Two time series running in parallel with a link between them, where the link is based on observation (Newman, 1998)



STELLA IN MOTION



STELLA IN MOTION



SSM, FORMALLY

Process Model

Process Error

$$x_t = f(x_{t-1}) + \varepsilon_t$$

$$y_t = g(x_t) + \varepsilon_t$$

Observation Model

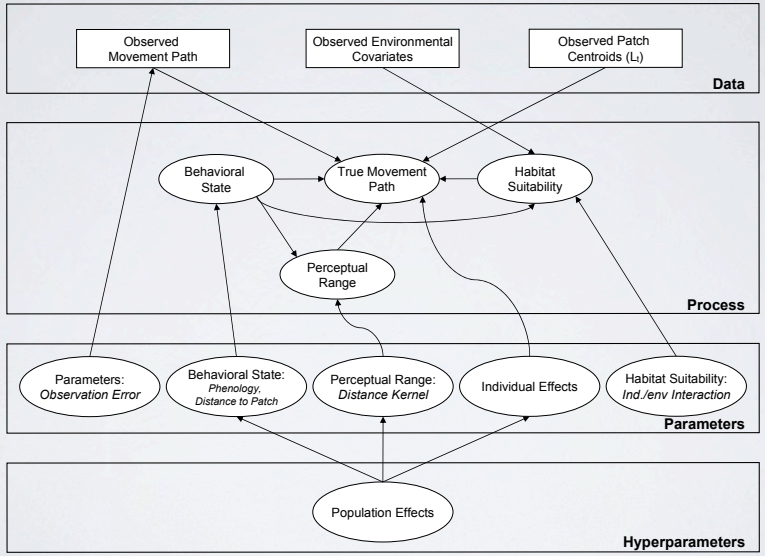
Observation Error

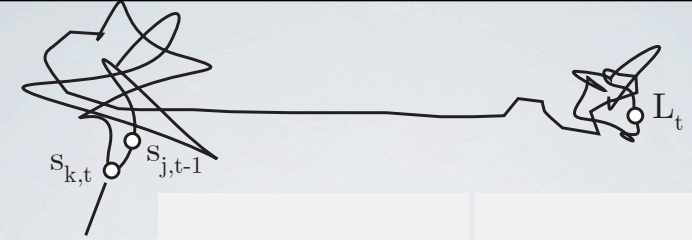
Jonsen et al., (2003), Ecology; Jonsen et al., (2005), Ecology; Patterson et al., (2008), TREE.

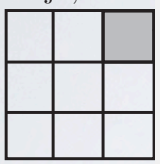
INFERENTIAL MODELS: WHY A NEW MODEL?

- We have increasing amounts of data – our ability "collar 'em and follow 'em" has outpaced our analytical ability
- We have increasingly finer resolution data for both movement and for the environment
- Many previous models are based on CRWs:
  - We wanted to account for more behavior in the process model

OUR NEW MODEL







$$p(\beta_m, m \mid \mathbf{z}) \propto \prod_{i=1}^{n} \prod_{t=1}^{T} Multinom(z_{ijk,t,m}|1, \theta_{ijk,t-1,m}) \cdot \mathcal{N}_t(0, \sigma^2)$$

WHAT DOES THAT GET US THAT LOOKING AT THE MAP DOESN'T?

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PNAS

A movement ecology paradigm for unifying organismal movement research

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Benjamin D. Dalziel,[1,*] Juan M. Morales,[2,†] and John M. Fryxell[1,‡]

- Ability to incorporate complex spatial behavior, e.g. memory, fidelity

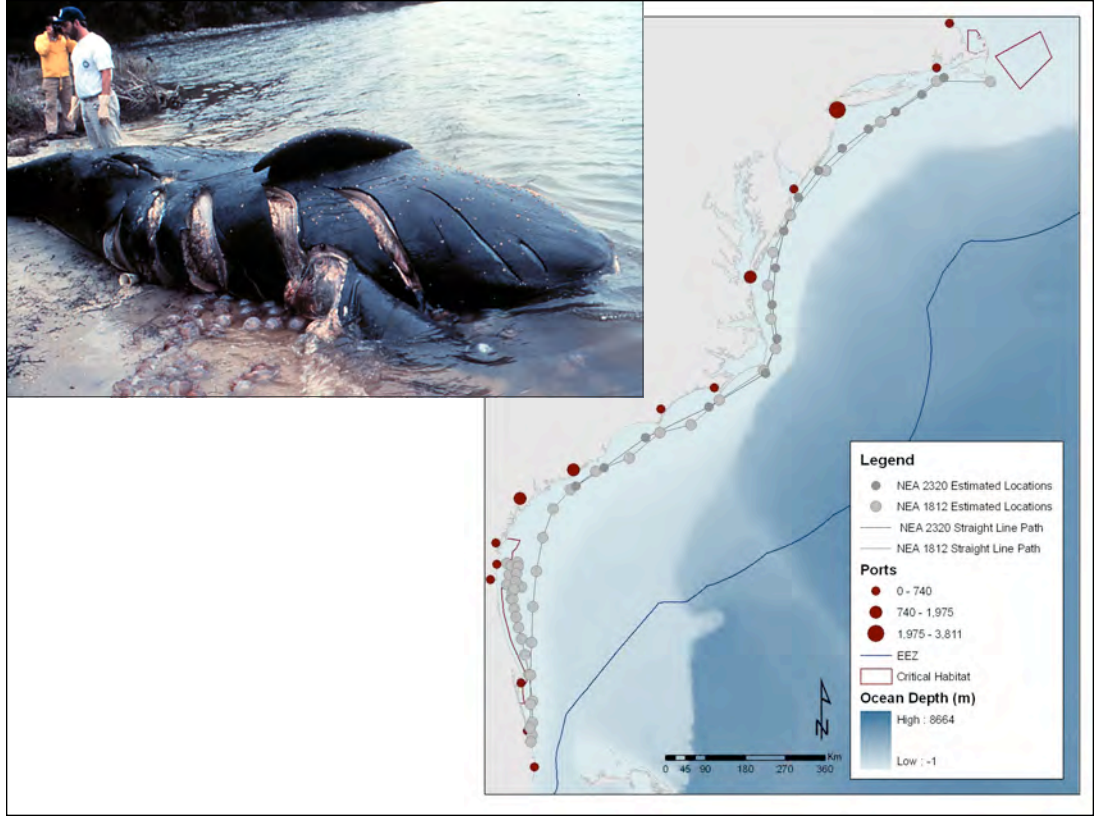
Schick et al., (2008), Ecology Letters 11:1138-1150

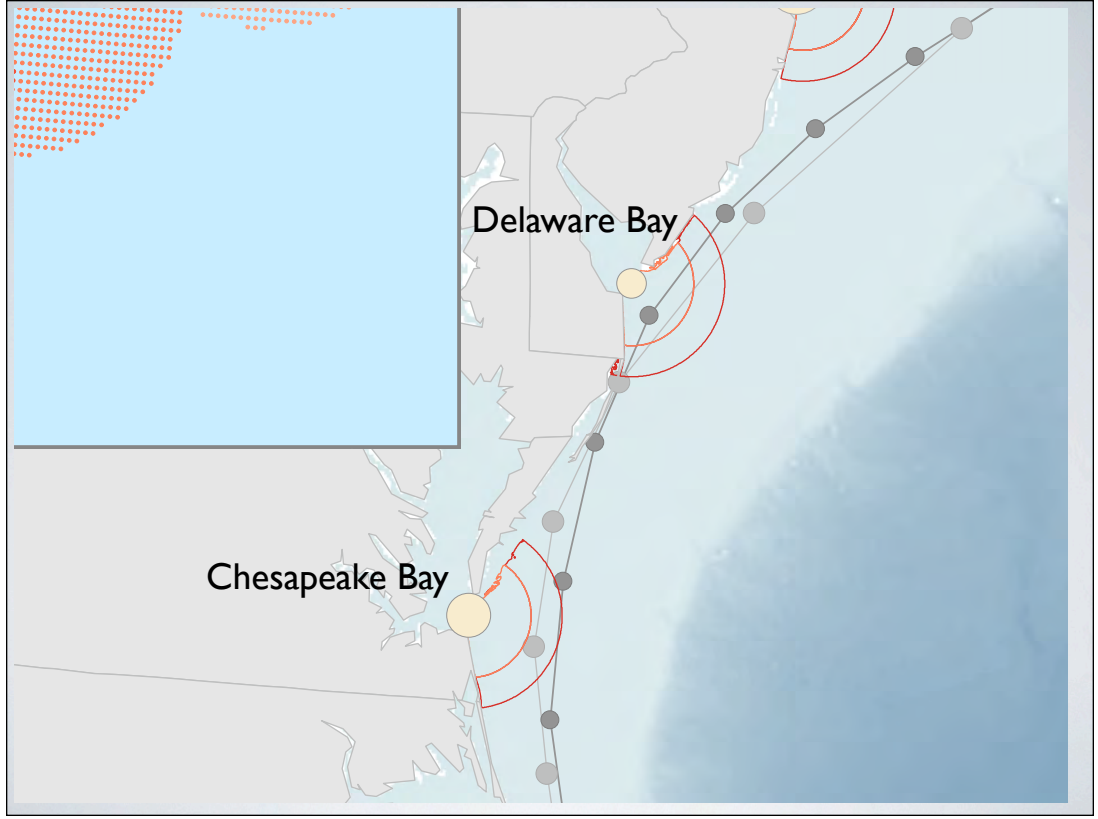
APPLYING THE MODEL

- North Atlantic Right Whales
  - How do they perceive their habitat in the migratory corridor?

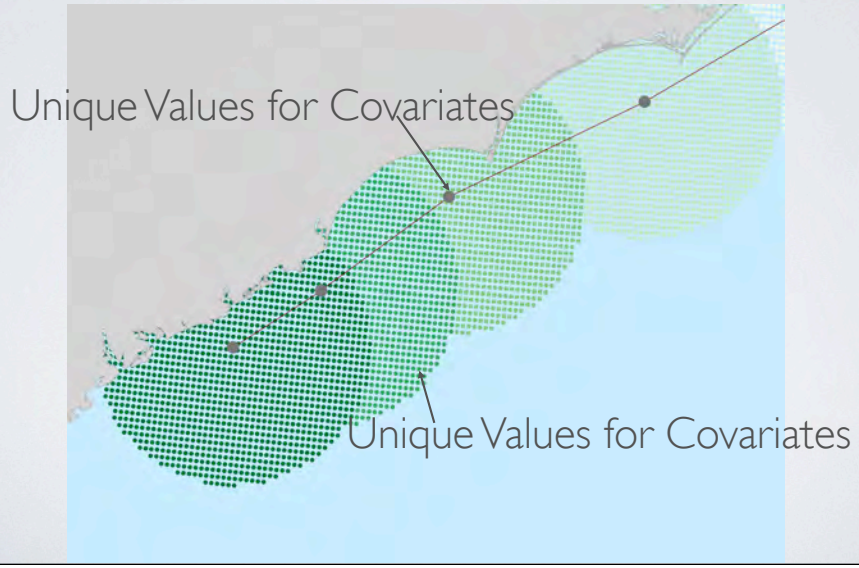
STRIKING THE *RIGHT* BALANCE IN RIGHT WHALE CONSERVATION

- 300-400 right whales remain
- Despite many years of protection and study, their population is vulnerable, especially in the migratory corridor
- 26% of ship strike mortalities happen in this area
- Previous work:
  - Photo-mark recapture of individuals (~250 sightings); outer limit of sightings was about 40 nautical miles
  - Has modeled Latitude as a function of day of year (Firestone et al, 2008)
- How then, do migrating right whales perceive this habitat?


Legend
NEA 2320 Estimated Locations
NEA 1812 Estimated Locations
NEA 2320 Straight Line Path
NEA 1812 Straight Line Path
Ports
0 - 740
740 - 1,975
1,975 - 3,811
EEZ
Critical Habitat
Ocean Depth (m)
High : 8664
Low : -1
0 45 90 180 270 360
Km

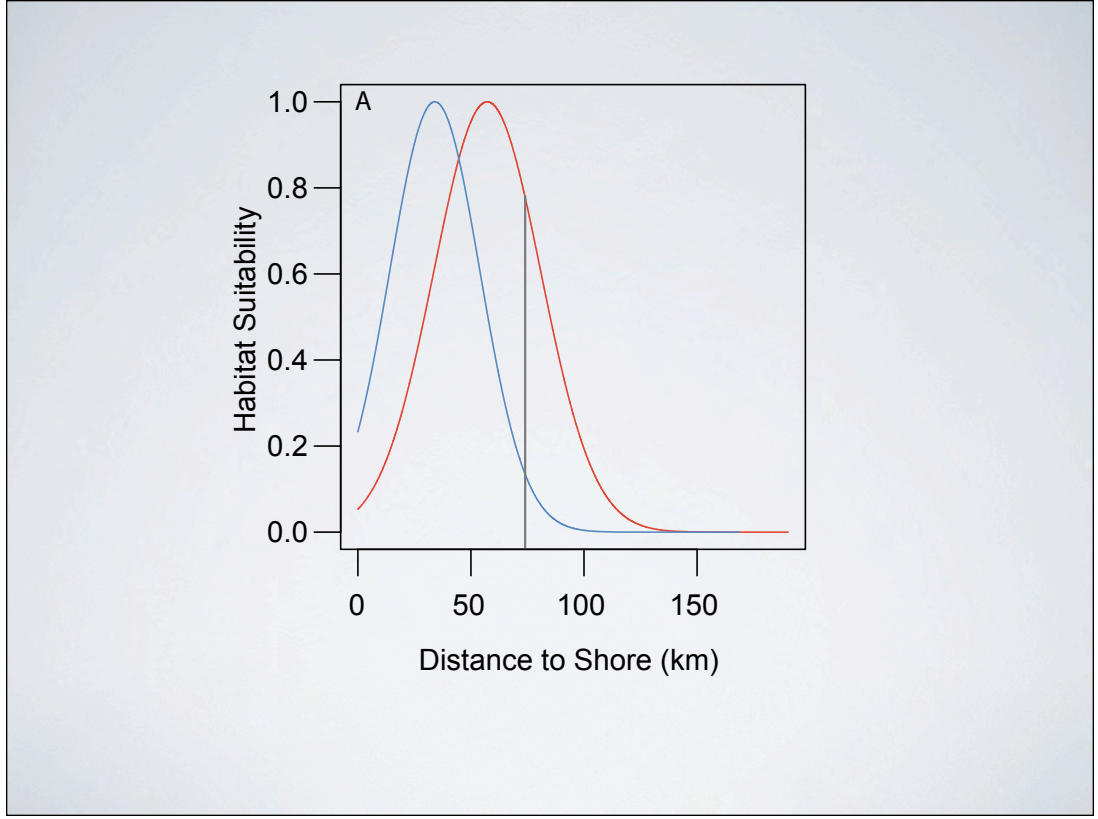

Delaware Bay
Chesapeake Bay

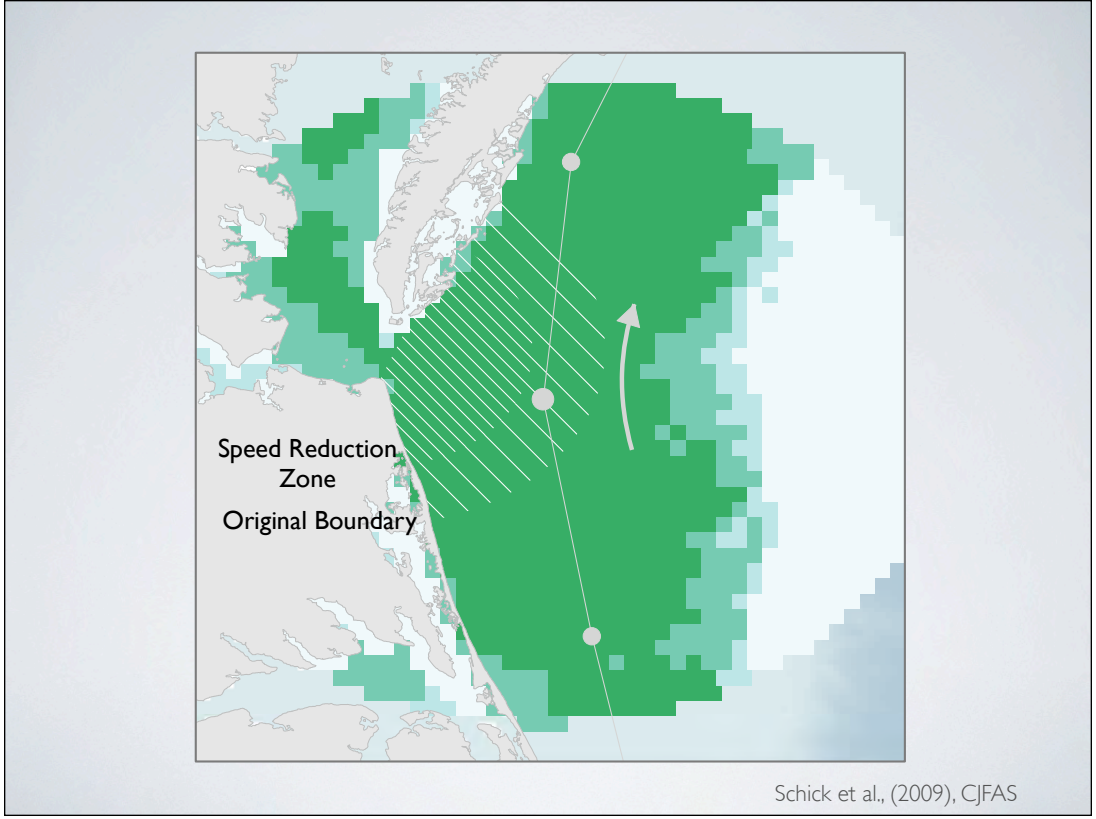
Creating the 'Tube'



RESULTS

- Posterior estimate of the β's
- Habitat suitability as a function of 1) distance to shore and 2) depth
  - Hold other covariates fixed at their mean value, and calculate *h* as a function of the covariate of interest
- Habitat suitability in and around select ports


A
1.0
0.8
0.6
0.4
0.2
0.0
Habitat Suitability
0
50
100
150
Distance to Shore (km)



Schick et al., (2009), CJFAS

SUMMARY

- Movement is cool
- Modeling it is hard, but can yield interesting ecological and conservation answers to complicated questions
- Since it's hard, make sure that you'll gain inference on the movement process by moving beyond 'the map'

ACKNOWLEDGEMENTS

- Funding:
  - James B Duke Fellowship
  - DUML Harvey Smith Dissertation Year Fellowship
  - SERDP/DoD Grant (W912HQ-04-C-0011) to AJ Read and PN Halpin
- Organizing Committee for including me


Questions?