Machine Learning for Computational Sustainability

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and the Cornell Lab of Ornithology
Data \rightarrow Models \rightarrow Policies

- Managing Earth’s ecosystems is a control problem
- We need
  - A model of the “plant”
  - An optimal controller
- Our research:
  - Machine learning methods for modeling ecosystem dynamics from data
  - Approximate Stochastic Dynamic Programming algorithms for creating optimal controllers
Outline

- Model of the plant
  - Towards a Dynamical Model of Bird Migration
- Optimal control
  - Managing wildfire in Eastern Oregon
  - Managing invasive plant species in the US Intermountain West
Bird Distribution and Migration

- **Management:**
  - Many bird populations are declining
  - Predicting aircraft-bird interactions
  - Siting wind farms
  - Night-time lighting of buildings (esp. skyscrapers)
  - How will climate change affect bird migration and survival?

- **Science:**
  - What is the migration decision making policy for each species
    - When to start migrating?
    - How far to fly each night?
    - When to stop over and for how long?
    - When to resume flying?
    - What route to take?
Why bird migration is poorly understood

- It is difficult to observe
  - Takes place at continental scale (and beyond)
  - Impossible for the small number of professional ornithologists to collect enough observations
  - Very few birds have been individually tracked
What Data Are Available?

- Birdwatcher count data: eBird.org
- Doppler weather radar
- Night flight calls
eBird Data

- Bird watchers record their observations in a database through eBird.org.
  - “Citizen Science”
- Dataset available for analysis
- Features
  - LOTS of data!
    - ~3 million observations reported last May
  - All bird species (~3,000)
  - Year-round
  - Continent-scale
- Challenges
  - Variable quality observations
  - No systematic sampling design
Doppler Weather Radar

- Weather radar detects migrating birds

- Can estimate total biomass
- No species information
- Archived data available back to 1995
Night Flight Calls

- Many species of migrating birds emit flight calls that can be identified to species or species group
- New project at Cornell to roll out a large network of recording stations
- Automated detection and classification
- DTW kernel
  - Damoulas, et al, 2010
  - Results on 5 species
  - Clean recordings

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Bird Migration Modeling

- Given observations from ebird, radar, flight calls
  - Reconstruct migration behavior

- Given observations + weather forecast
  - Predict migration behavior for next 24 hours, next 5 days
Machine Learning Challenge

- Migration most naturally described at level of individual behavior, but we can only observe population-level statistics
  - We need a modeling technique to link the two

- Our Approach: Collective Graphical Models
Modeling Approach

- Place a grid of cells over North America
- State of a bird at time $t = \text{cell it occupies at time } t$

<table>
<thead>
<tr>
<th>Cell</th>
<th>Time</th>
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<tbody>
<tr>
<td>A</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
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Aggregate data: does not track individual birds
Hidden Markov Model

- Let $n^s_t(i)$ be the number of species $s$ in cell $i$ at time $t$
- Let $n^s_t$ be a vector of $n^s_t(i)$ across all cells $i = 1, ..., N$
- HMM dynamics: $P(n^s_t|n^s_{t-1}, x_t)$
  - $P(n^s_t(i)|n^s_t, x_t)$ is the probability distribution of the number of birds in cell $i$ at time $t$ given the locations of the birds in all previous cells in the previous time step $t-1$
  - $x_t$ is a vector of attributes describing system inputs (weather, temperature, wind, vegetation) that influence bird behavior
- HMM observations: eBird counts, radar, acoustic detections
Diagram of the Migration Model

- Species $s$
- Observers $o$
- Sites $i$
- Acoustic stations $k$
- Radar sites $v$

\[ x_t^s(i, o) \]
\[ y_{t,t+1}^s(k) \]
\[ z_{t,t+1}(v) \]
HMM with added features

\[ n_t^s \]

\[ w_t \]

\[ w_{t,t+1} \]

\[ x_t^s(i,o) \]

\[ y_{t,t+1}(k) \]

\[ z_{t,t+1}(v) \]

\[ n_t^s \]

\[ n_{t,t+1}^s \]

\[ s = 1, \ldots, S \]

\[ o = 1, \ldots, O(i,t) \]

\[ s = 1, \ldots, S \]

\[ i = 1, \ldots, L \]

\[ k = 1, \ldots, K \]

\[ v = 1, \ldots, V \]

birds

eBird

acoustic

radar
Computational Challenge

- Inference in this HMM is intractable
  - Population size > 5 Billion
- Solution: Gibbs Sampling over the “bird flows” in the HMM
- Sheldon & Dietterich (NIPS 2011) presents a fast Gibbs sampler that takes time independent of the population size
Results

- Running time

  - Running time independent of population size
  - Previous best: exponential

Best exact method (cubic in $M$)

Our method (to 2% relative error)

[Sheldon & Dietterich, NIPS 2011]
Bird Migration Summary

- Fitting Dynamical Models to Multiple Data Sources
  - eBird + radar + night flight calls
  - Collective Graphical Models: General Methodology
  - Fast Gibbs sampler for CGMs (independent of population size)

- Stay tuned for BirdCast
- Follow our progress at www.ebird.org
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Managing Wildfire in Eastern Oregon

- Natural state (hypothesized):
  - Large Ponderosa Pine trees with open understory
  - Frequent “ground fires” that remove understory plants (grasses, shrubs) but do not damage trees

- Fires have been suppressed since 1920s
  - Large stands of Lodgepole Pine
  - Heavy accumulation of fuels in understory
  - Large catastrophic fires that kill all trees and damage soils
  - Huge firefighting costs and lives lost
Study Area: Deschutes National Forest

- Goal: Return the landscape to its “natural” fire regime

- Management Question:
  - LET-BURN: When lightning ignites a fire, should we let it burn?

- ~4000 management units
LET BURN

- Model of System Dynamics
  - Model of lightning strikes and fire ignitions
  - Model of fire spread (suppressed or not suppressed)
  - Model of fire duration (suppressed or not suppressed)
  - Model of suppression costs
  - Model of forest growth (including fuel accumulation)

- For year = 1, ..., 100
  - For fire = 1, ..., NFires
    - ignite fire
    - decide whether to SUPPRESS or LET BURN (control input)
    - burn fire
  - Grow vegetation

- Objective: Expected discounted benefit
Expected Benefit of LETBURN (Suppress all fires after year 1)

Monte Carlo samples, $n = 1, \ldots, 500$

$\pm 1 \text{ s.d.}$

$E[B]$
Next Steps

- Single Year LETBURN Study:
  - Several model improvements
  - Include standard forest harvest policy
  - Include more accurate timber value

- 100-year Dynamic LETBURN Study
  - Needed: Approximate Dynamic Programming algorithms that can scale to immense state space
    - 4000 management units
    - Each unit in one of 25 states
    - $25^{4000}$ possible states
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Invasive Species Management in River Networks

- Tamarisk: invasive tree from the Middle East
  - Out-competes native vegetation for water
  - Reduces biodiversity

- What is the best way to manage a spatially-spreading organism?
System Dynamics

- Tree-structured river network
  - Each edge has H “sites” where a tree can grow.
  - Each site can be
    - {empty, occupied by native, occupied by invasive}

- In each time period:
  - Natural death
  - Seed production
  - Seed dispersal (preferentially downstream)
  - Seed competition to become established

- Management actions
  - {do nothing, eradicate, restore, eradicate+restore}
Economic Model

- Minimize expected discounted costs (sum of cost of invasive plus cost of management)

- Subject to annual budget constraint
Algorithm

- Approximate computation of transition probabilities
  - Exact computation is intractable
  - Compute highly-accurate Monte Carlo estimates from simulator
  - [This is actually the rate-limiting step]
- Exact solution via value iteration
- Large memory: 14 Billion state-action combinations
Rule of Thumb Policies (from literature)

- **Triage Policy**
  - Treat most-invaded edge first
  - Break ties by treating upstream first

- **Leading edge**
  - Eradicate along the leading edge of the invasion

- **Chades, et al.**
  - Treat most-upstream invaded edge first
  - Break ties by amount of invasion

- **Optimal**
  - Our exact solution to the control problem
Cost Comparisons: Rule of Thumb Policies vs. Optimal

**Total Costs**

- **Large pop, up to down (Triage)**: 375
- **Chades**: 350
- **Leading Edge**: 400
- **Optimal**: 275

ICGG 2012
Summary

- Model of the plant
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- MCMC algorithm for inference in Collective Hidden Markov Model
  - eBird + radar + acoustics

- Approximate Dynamic Programming using Monte Carlo trials

- Exact Dynamic Program using Monte Carlo estimates of transition probabilities
Acknowledgements

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  - Wildfire management
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