Machine Learning for Computational Sustainability

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Data → Models → 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

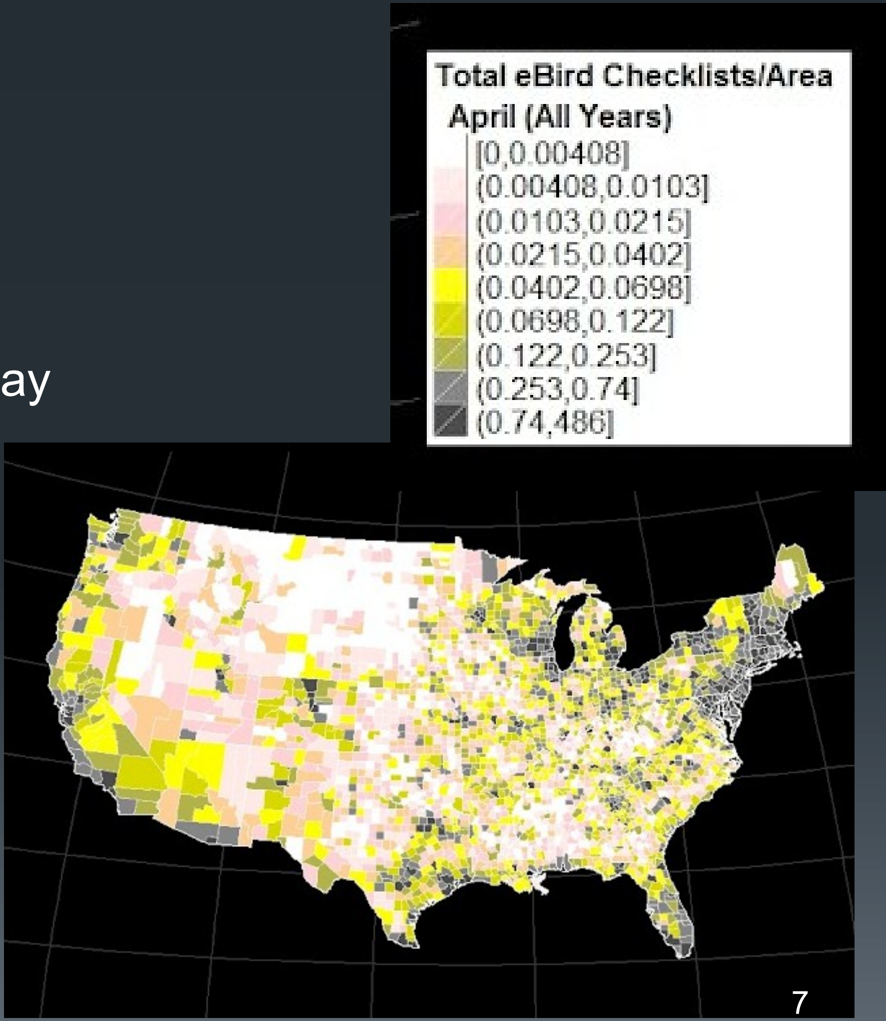
- It is difficult to observe
  - Takes place at continental scale (and beyond)
  - Impossible for the small number of professional ornithologists to collect enough observations
  - Very few birds have been individually tracked

What Data Are Available?

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

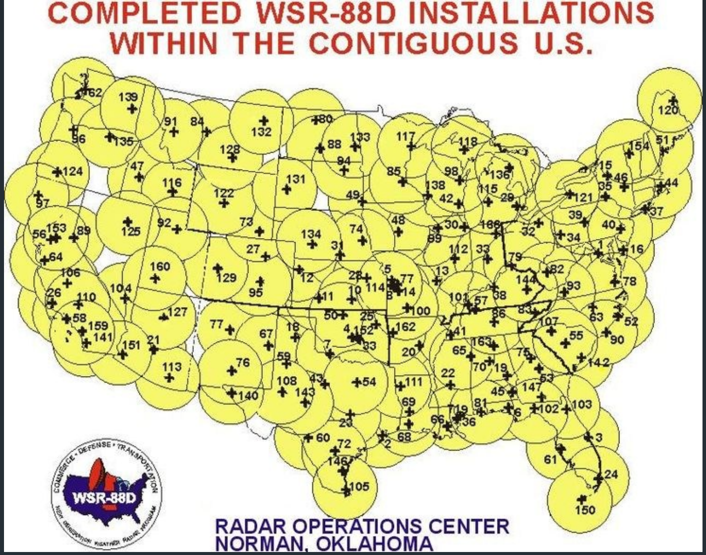
eBird Data

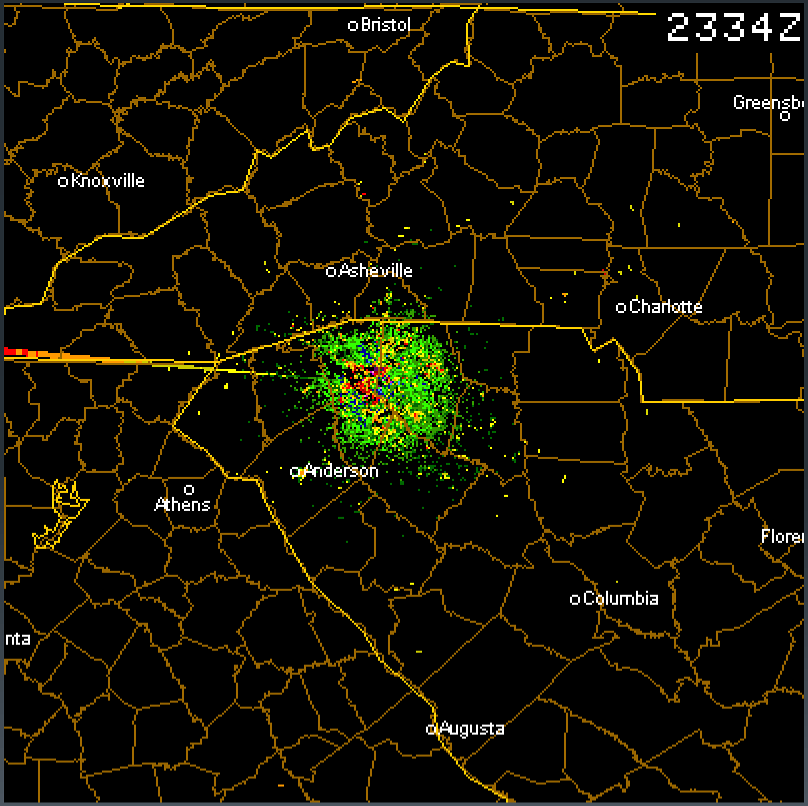
- Bird watchers record their observations in a database through eBird.org.
  - “Citizen Science”
- Dataset available for analysis
- Features
  - LOTS of data!
    - ~3 million observations reported last May
  - All bird species (~3,000)
  - Year-round
  - Continent-scale
- Challenges
  - Variable quality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



Doppler Weather Radar

- Weather radar detects migrating birds

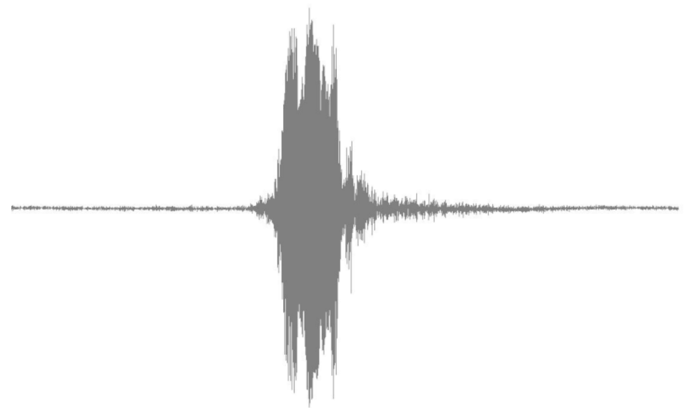


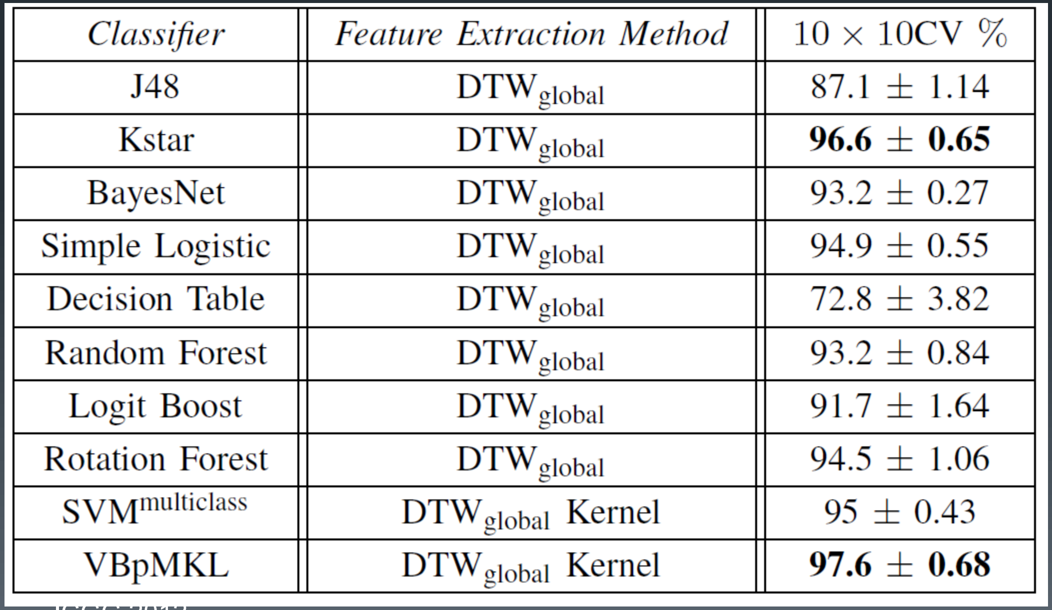


- Can estimate total biomass
- No species information
- Archived data available back to 1995

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





Classifier	*Feature Extraction Method*	$10 \times 10\text{CV}$ %
J48	$\text{DTW}_{\text{global}}$	87.1 ± 1.14
Kstar	$\text{DTW}_{\text{global}}$	$\mathbf{96.6 \pm 0.65}$
BayesNet	$\text{DTW}_{\text{global}}$	93.2 ± 0.27
Simple Logistic	$\text{DTW}_{\text{global}}$	94.9 ± 0.55
Decision Table	$\text{DTW}_{\text{global}}$	72.8 ± 3.82
Random Forest	$\text{DTW}_{\text{global}}$	93.2 ± 0.84
Logit Boost	$\text{DTW}_{\text{global}}$	91.7 ± 1.64
Rotation Forest	$\text{DTW}_{\text{global}}$	94.5 ± 1.06
$\text{SVM}^{\text{multiclass}}$	$\text{DTW}_{\text{global}}$ Kernel	95 ± 0.43
VBpMKL	$\text{DTW}_{\text{global}}$ Kernel	$\mathbf{97.6 \pm 0.68}$

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

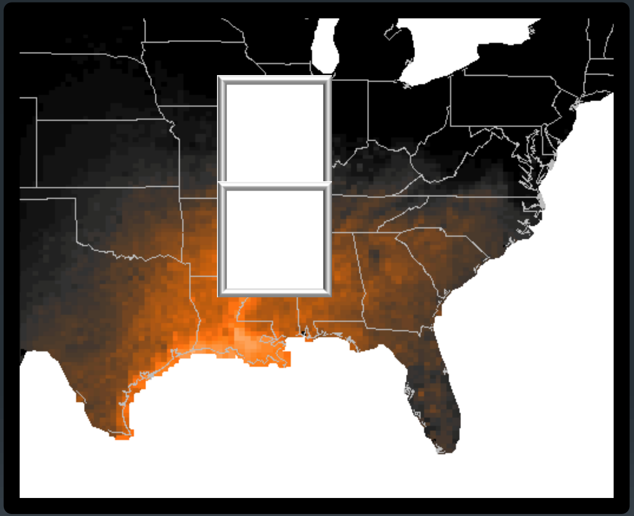
- Migration most naturally described at level of individual behavior, but we can only observe population-level statistics
  - We need a modeling technique to link the two
- Our Approach: Collective Graphical Models

Modeling Approach

- Place a grid of cells over North America
- State of a bird at time t = cell it occupies at time t

Time

Cell		1	2	3
	A	87	61	22
	B	13	39	78



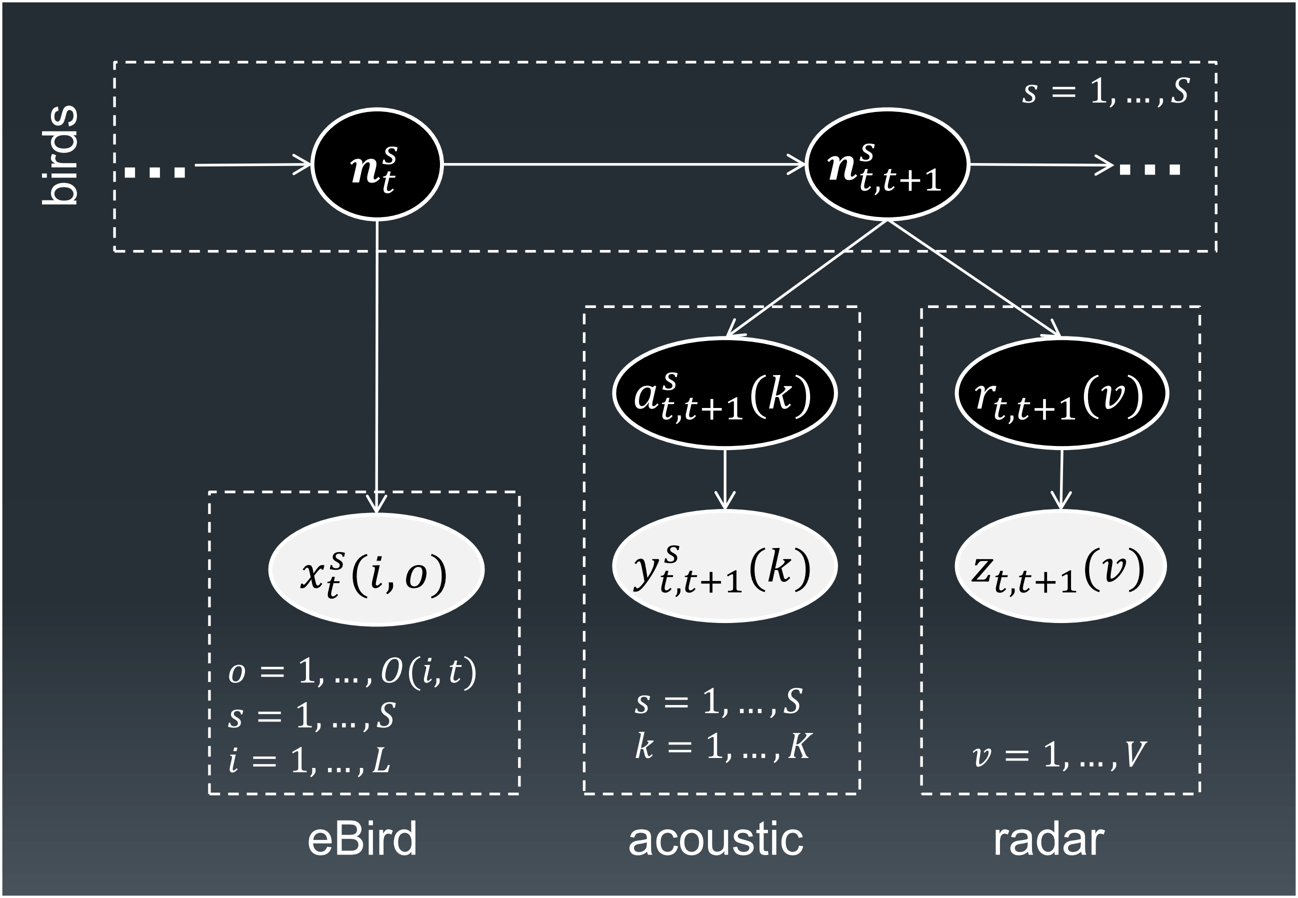
- Aggregate data: does not track individual birds

Hidden Markov Model

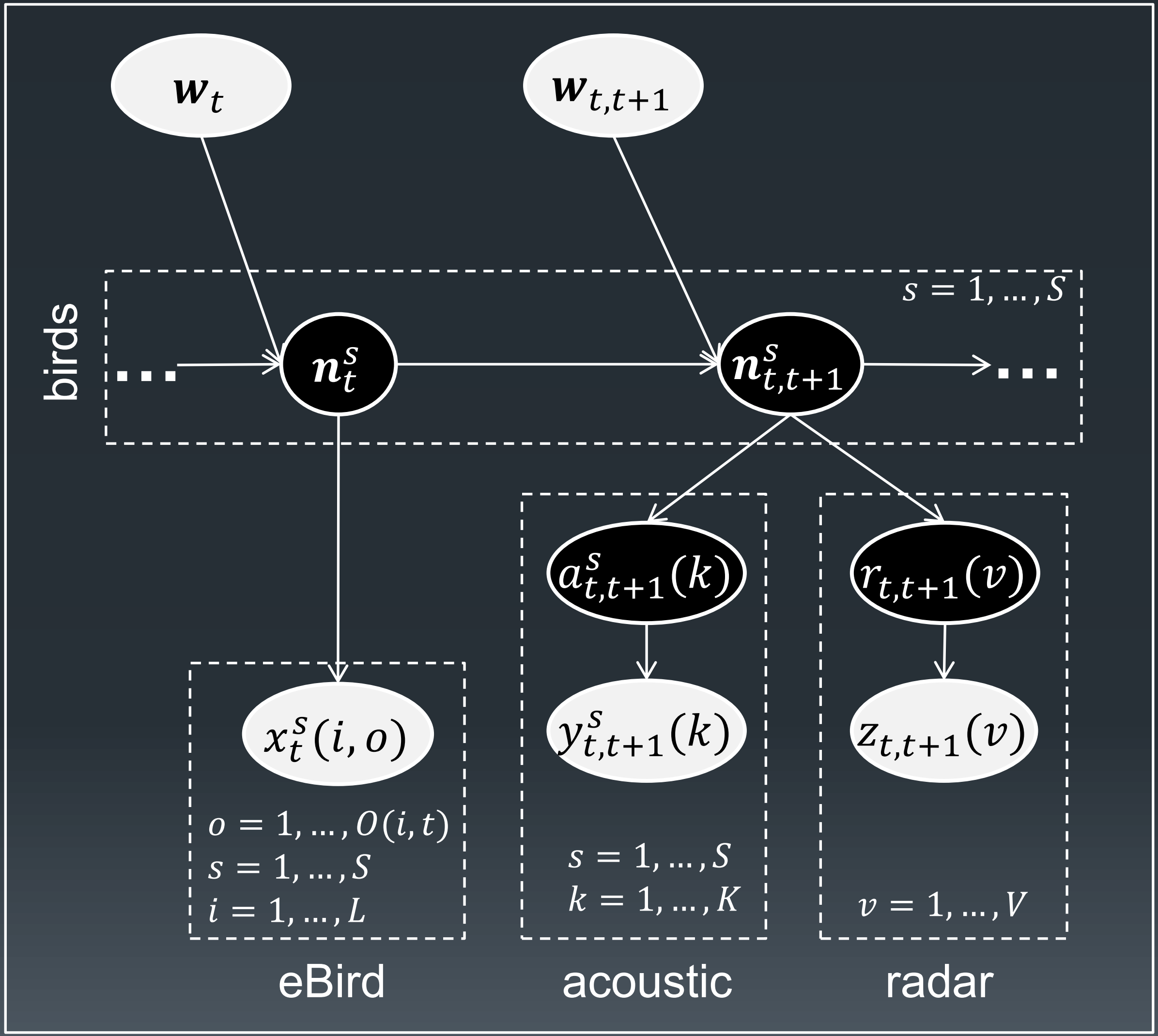
- Let $n_t^s(i)$ be the number of species s in cell i at time t
- Let $\boldsymbol{n}_t^s$ be a vector of $n_s^t(i)$ across all cells $i = 1, \dots, N$
- HMM dynamics: $P(\boldsymbol{n}_t^s | \boldsymbol{n}_{t-1}^s, \mathbf{x}_\mathrm{t})$
  - $P(n_t^s(i) | \boldsymbol{n}_t^s, \boldsymbol{x}_t)$ is the 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 $t - 1$
  - $\boldsymbol{x}_t$ 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



HMM with added features

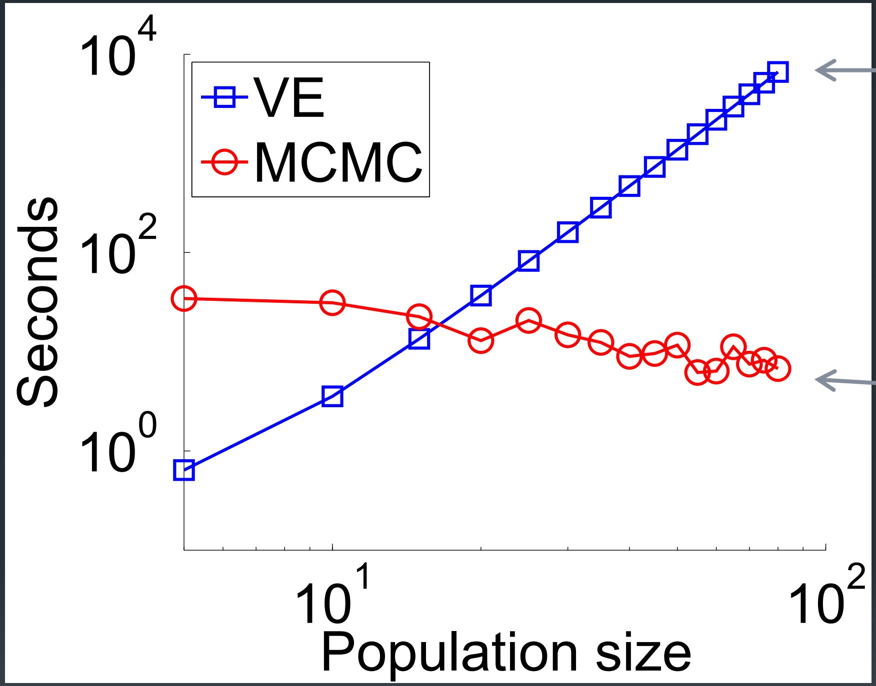


Computational Challenge

- 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



Best exact method
(cubic in M)

Our method
(to 2% relative error)

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

[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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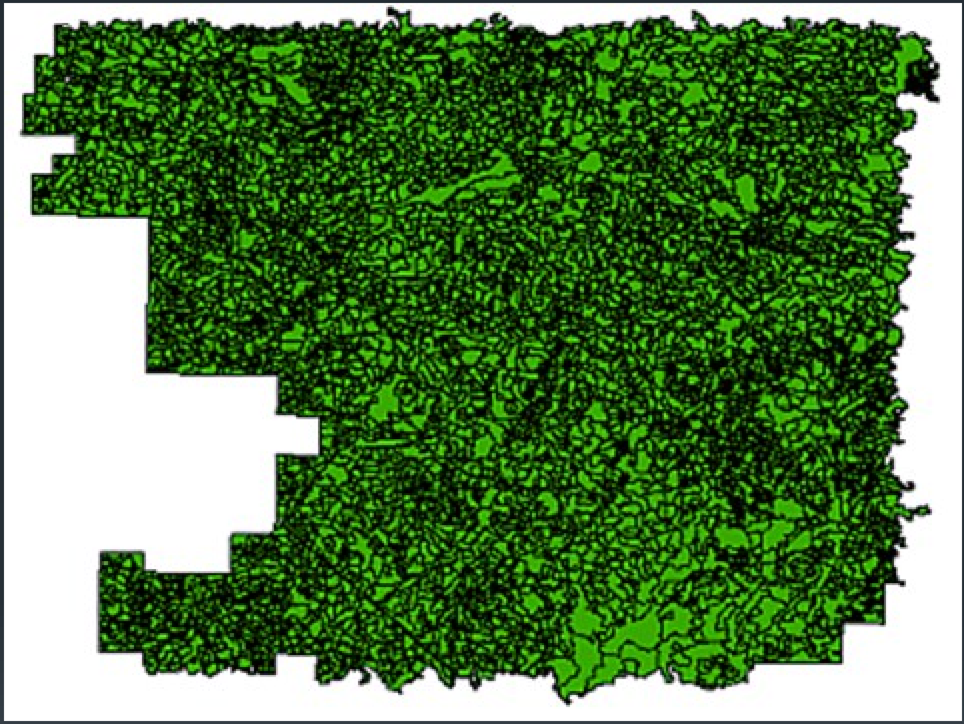
Managing Wildfire in Eastern Oregon

- 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



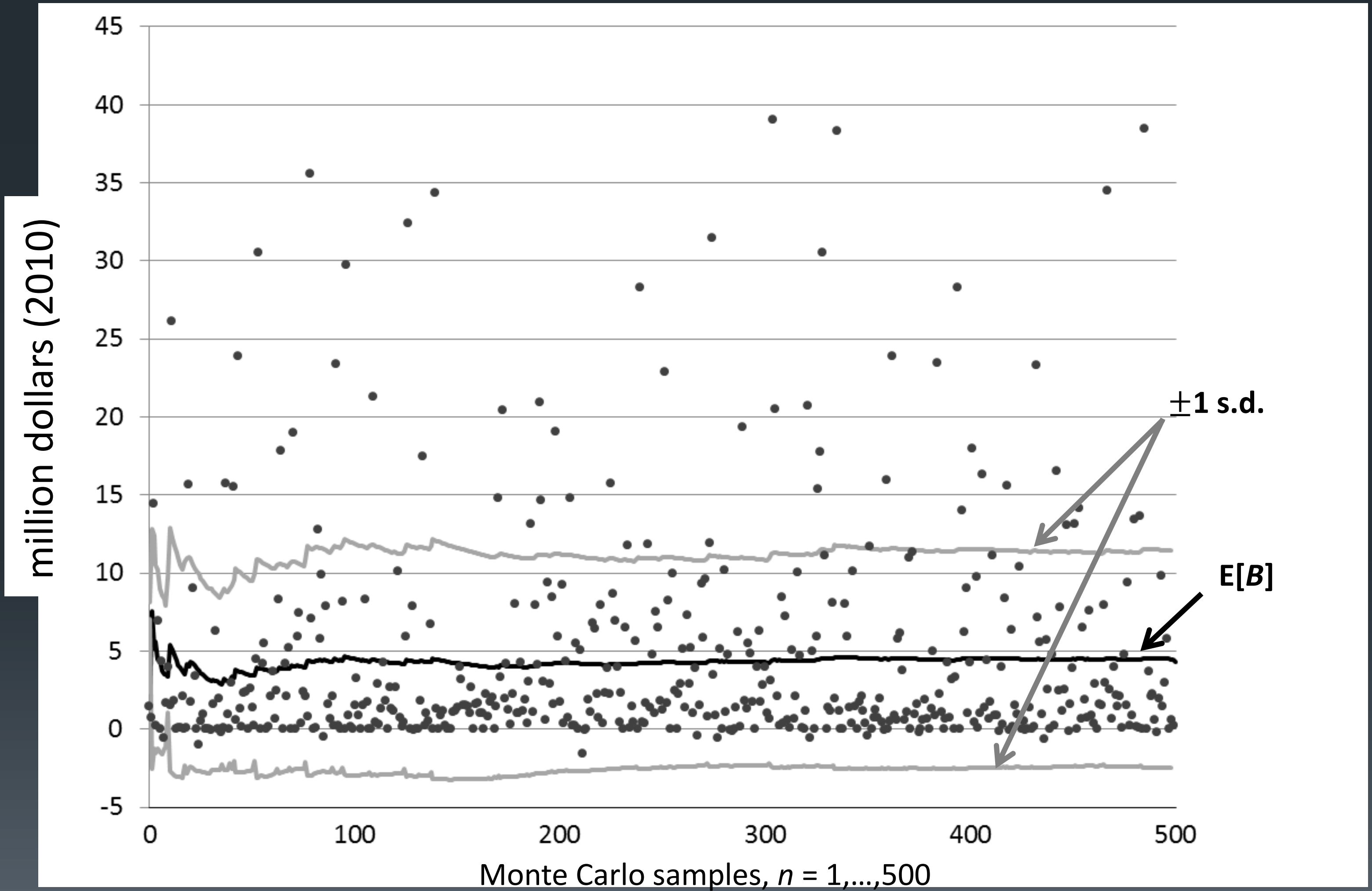
LET BURN

- 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)



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

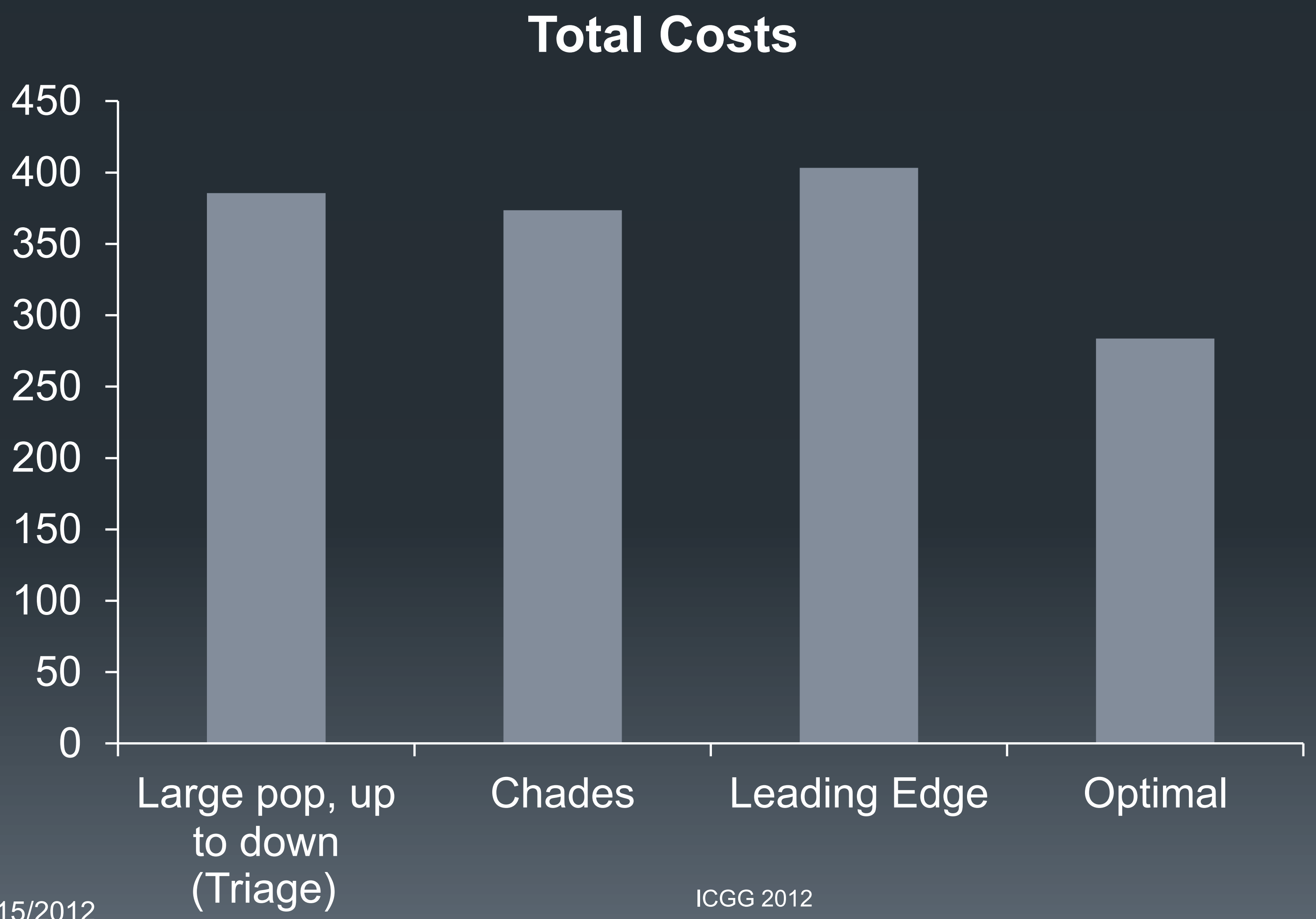
Algorithm

- 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



Summary

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- MCMC algorithm for inference in Collective Hidden Markov Mode
  - eBird + radar + acoustics
- Approximate Dynamic Programming using Monte Carlo trials
- Exact Dynamic Program using Monte Carlo estimates of transition probabilities

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- NSF Expeditions in Computing
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  - Invasive species management

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