AI for Conservation Decisions

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The biodiversity crisis

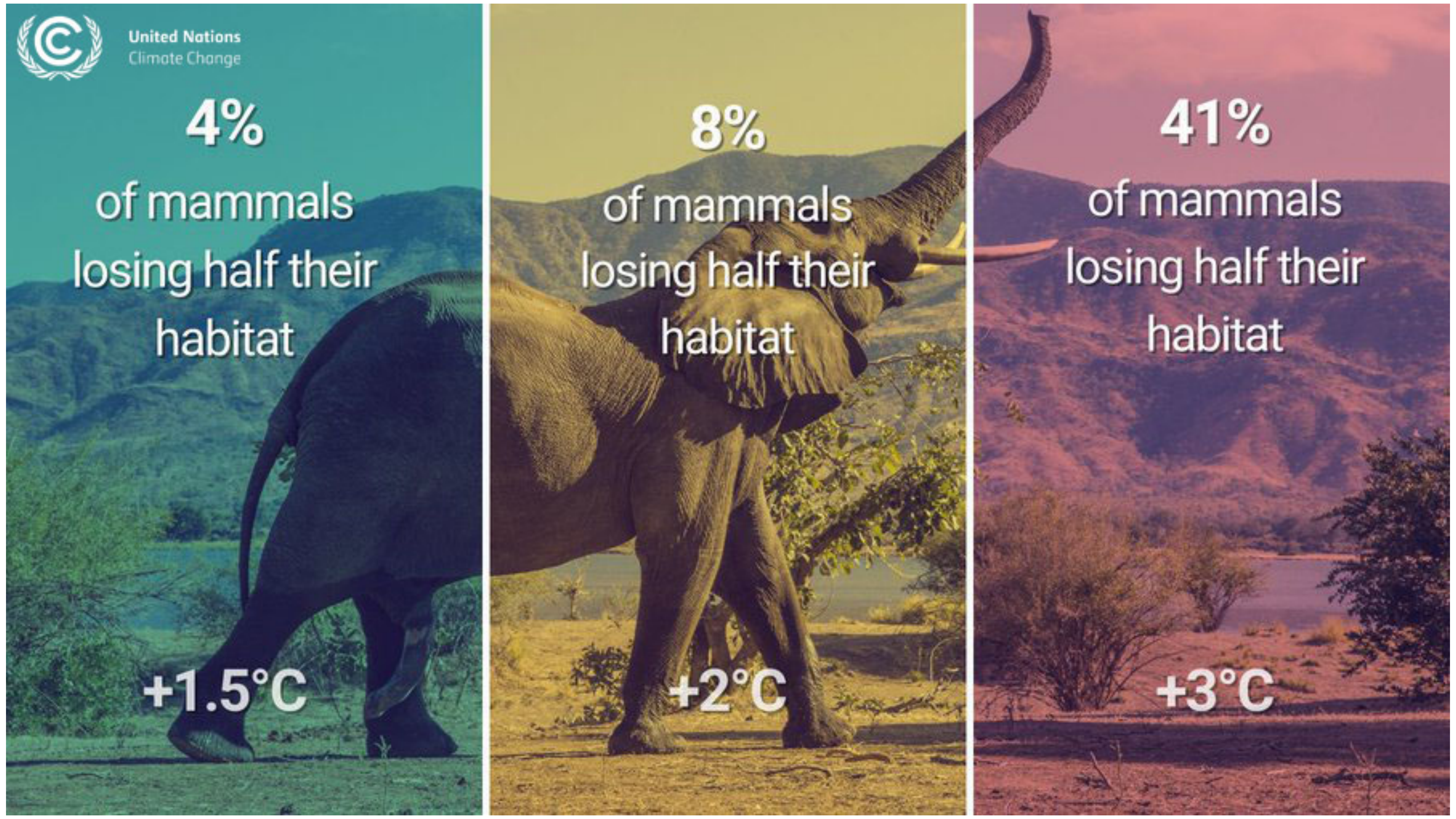
Photos from Bernard Spragg (Flickr) and WWF

69% decline in wildlife populations since 1970 [WWF 2022]

1 million species in danger of extinction [IPBES 2019]

The biodiversity crisis is a climate crisis

Climate impacts biodiversity

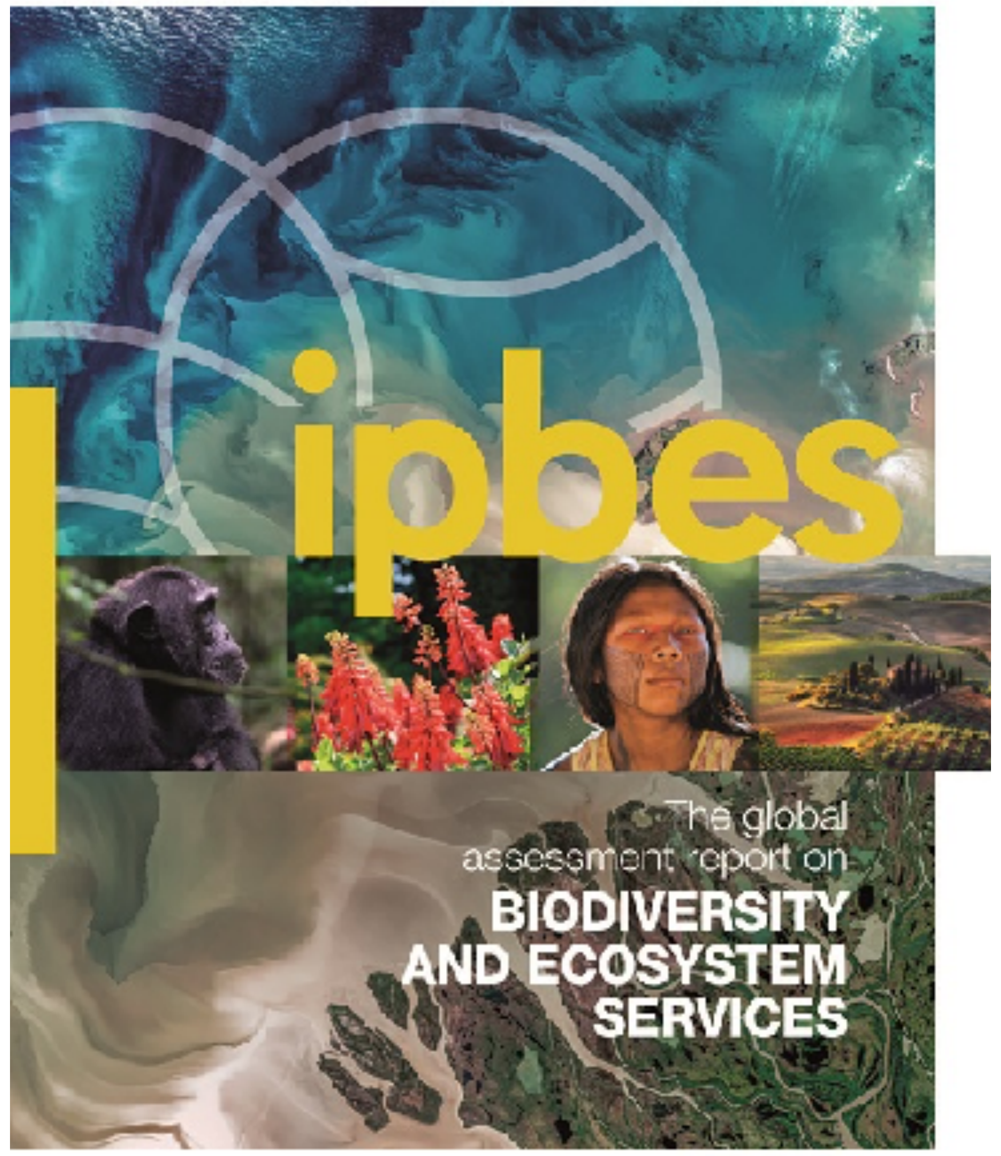


Biodiversity impacts climate

Contribute 37% of CO_2 mitigation necessary to keep to Paris Agreement

Griscom et al. (2017). Natural climate solutions. *PNAS*.

Biodiversity provides ecosystem services



ipbes

2019

iied International Institute for Environment and Development

Food and Agriculture Organization of the United Nations

WORLD ECONOMIC FORUM

Intact biodiversity helps mitigate climate change

land & ocean absorb half of all carbon emissions

deforestation turns the Amazon from a carbon sink into a carbon source

“landscape architects” like elephants create carbon stores

and provides broader ecosystem services

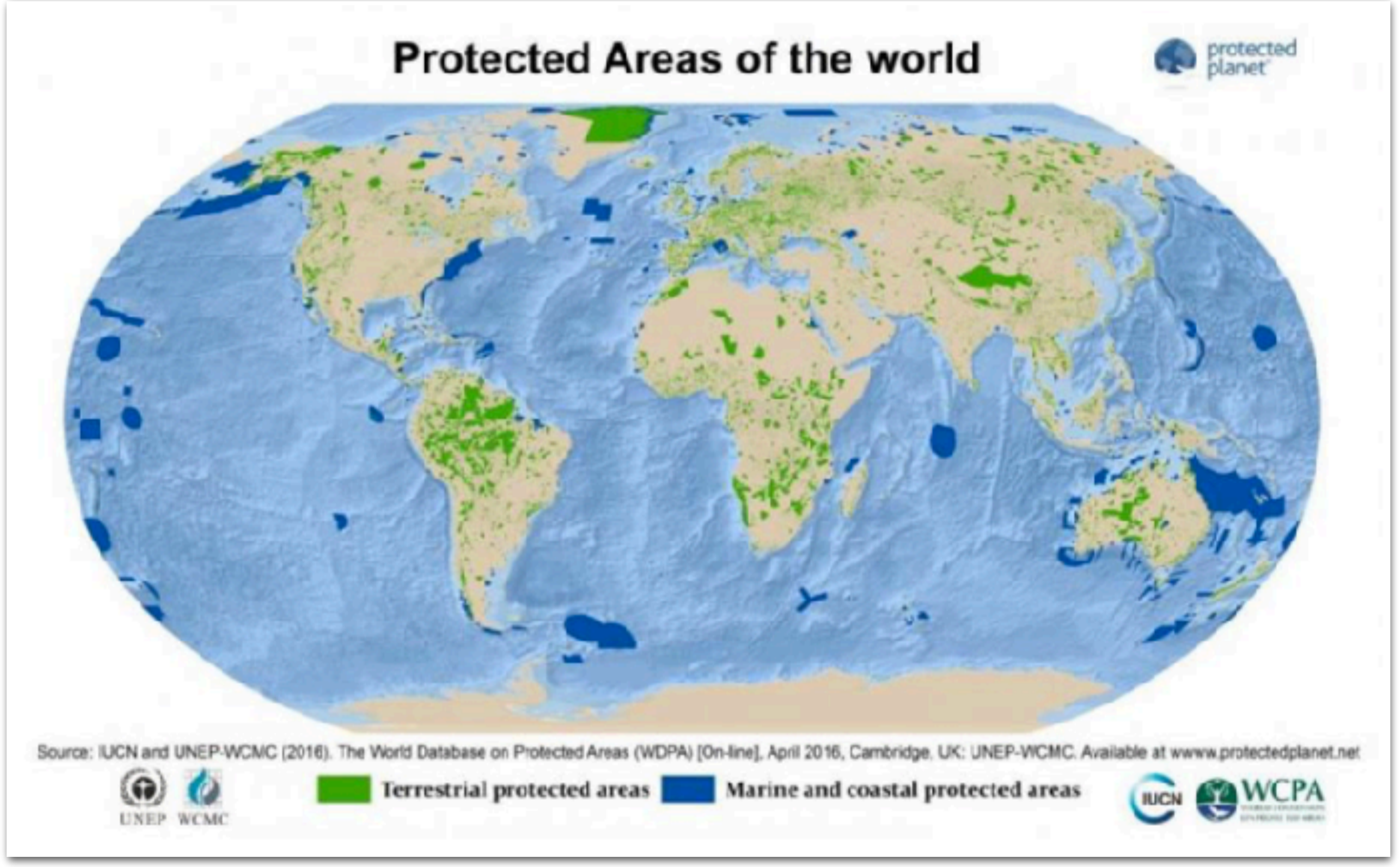
economic wellbeing: 1 billion people rely on forests for livelihoods

human health: deforestation and species shift create disease spillover

food security: wild meat and fish stocks

Global attention towards biodiversity

2022 United Nations Global Biodiversity Framework



30x30 Initiative

land: 17% → 30% protected

oceans: 8% → 30% protected

Biodiversity challenges & solutions

Question

What are some challenges we're facing with biodiversity conservation today?

5 main drivers of biodiversity loss

1. **Changes in land- and sea-use**

   Agriculture is the key driver, threatening more >85% of the 28,000 species at risk of extinction

2. **Direct exploitation of species**

   Logging (timber) and poaching (wild meat consumption, luxury goods, pet trade)

3. **Invasive species**

   Humans have introduced over 37,000 species with global economic cost of $423 billion/year

4. **Climate change**

   Biggest impacts on most vulnerable ecosystems: coral reefs, mountains (incl. glaciers), polar regions

5. **Pollution**

   Toxic insecticides, marine plastic pollution, nitrogen deposition

Conservation levers

- Protected areas (and “other effective area-based conservation measures”, OECMs)

  Land prioritization, threat management

- Promoting alternative livelihoods & education
- Human-wildlife conflict (→ coexistence)
- Species reintroduction and translocation
- Conservation financing

  Payments for ecosystem services, conservation auctions

- Indirect drivers

  Climate change, agriculture, water management, reduce poverty, support Indigenous rights

Overview of algorithmic decision making

What is the population of pygmy killer whale?

Is the population going up or down?

Which lands maximize protection for snow leopards?

What if we're budget-constrained?

Do community-managed areas reduce elephant poaching?

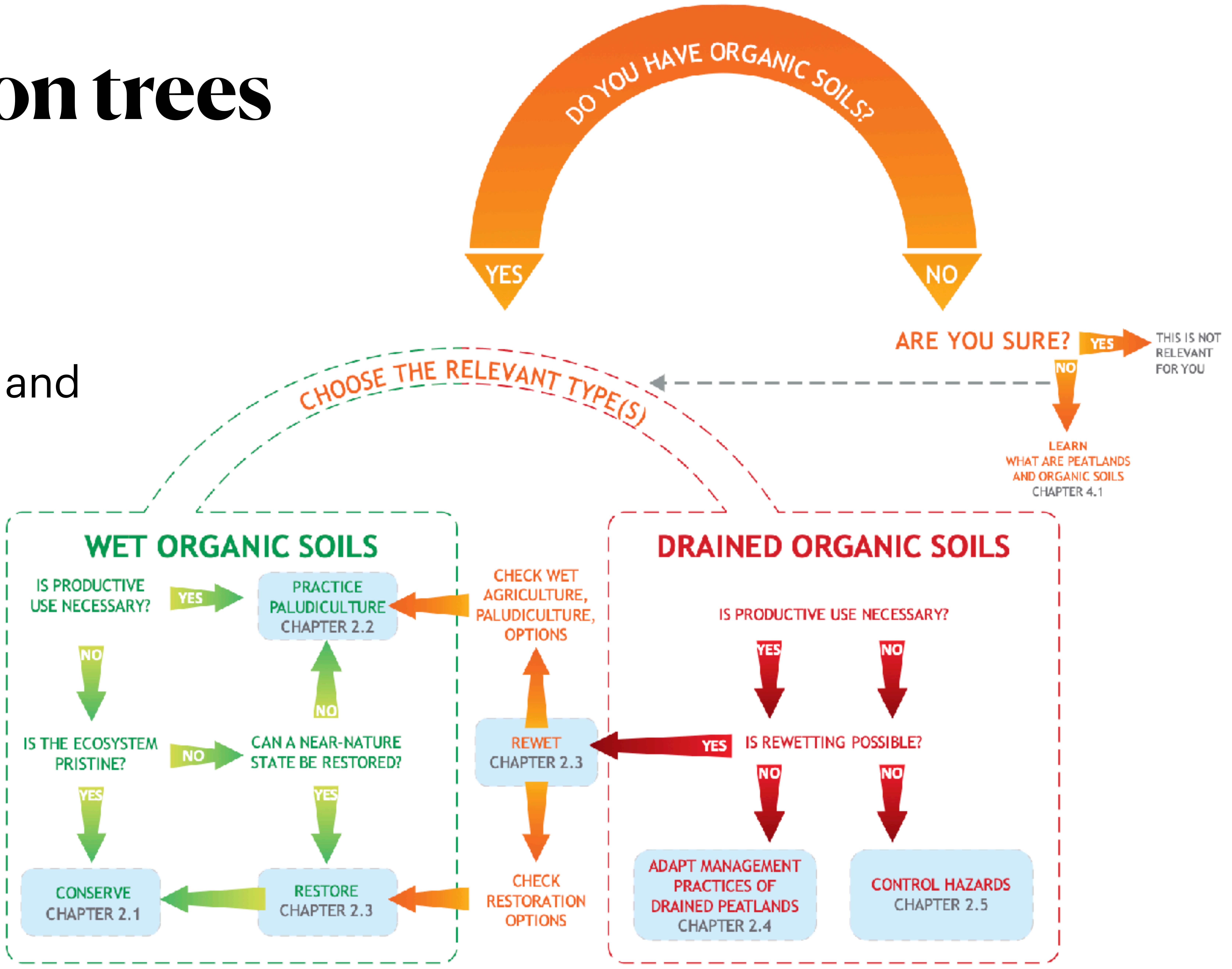
Photos from Wikimedia Commons


Monitoring
Planning
Impact evaluation
Data
Model
Decisions
Evaluation
Computer vision,
statistics
Optimization,
RL, OR
Causal inference,
economics
Our focus in this talk

Classic decision trees

US FAO

Decision support tree for management of peatlands and organic soils



Conservation decisions are hard

Effective decision-making is imperative

Limited resources

High-stakes, urgent settings

… but challenging

Global scale

Incomplete information
↳ uncertainty

Complex interaction effects

Many stakeholders & competing incentives

Question

What types of decision-making methods are you familiar with?

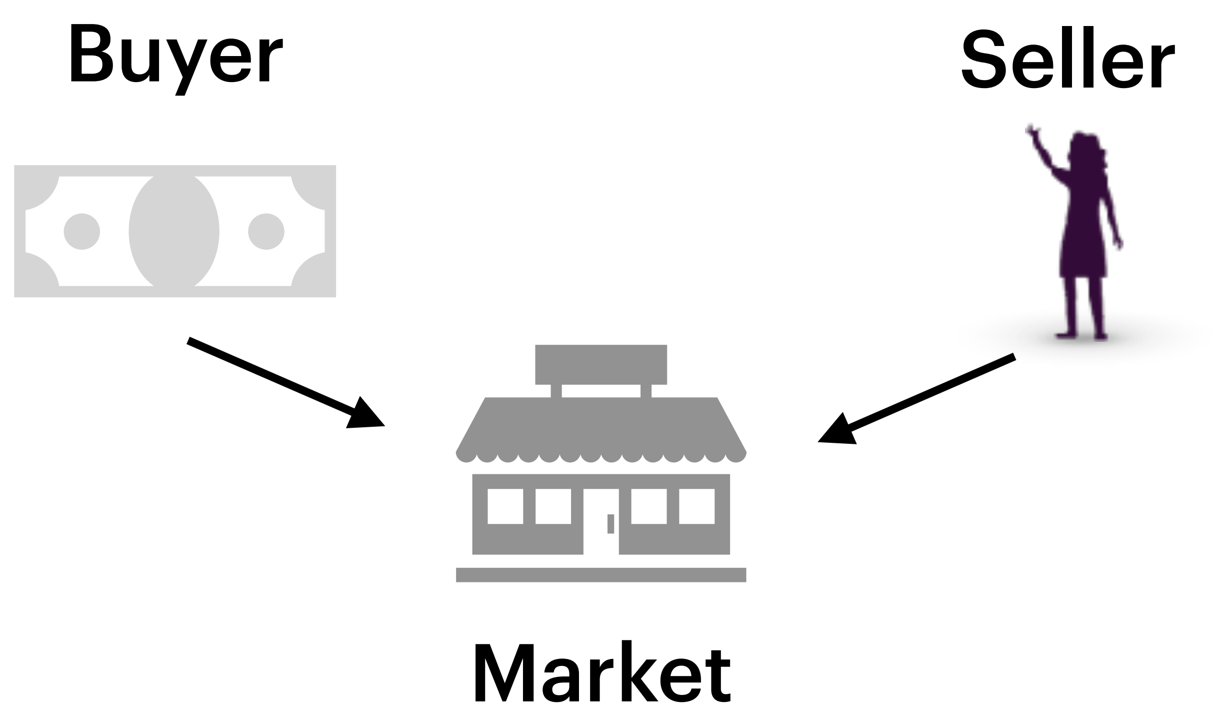
Key methods for decision making

Optimization

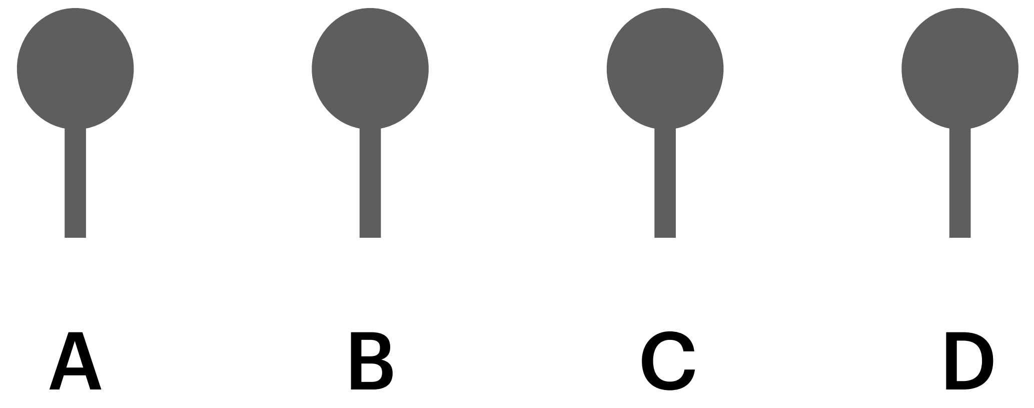
$$\max \quad f(x)$$

$$\text{subject to} \quad h_n(x), g_n(x)$$

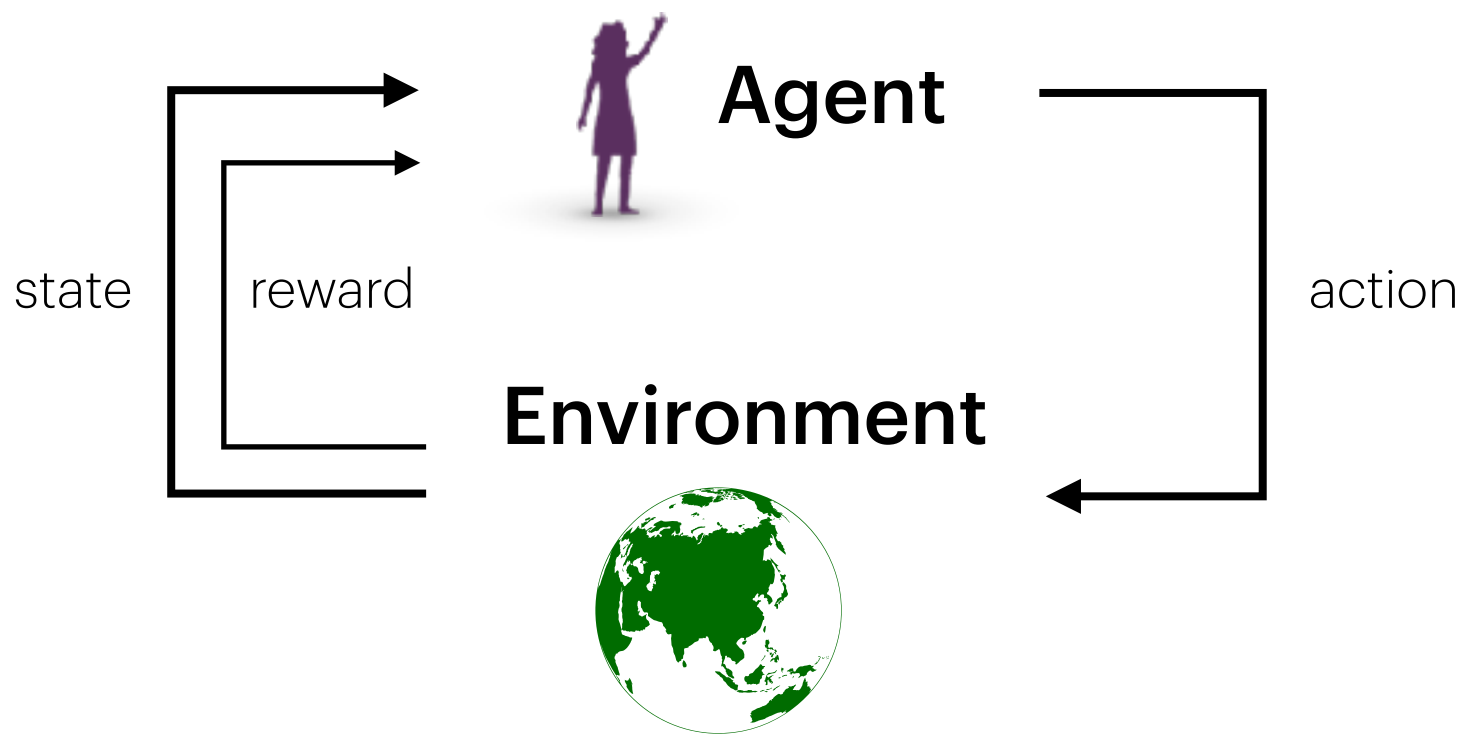
Market design



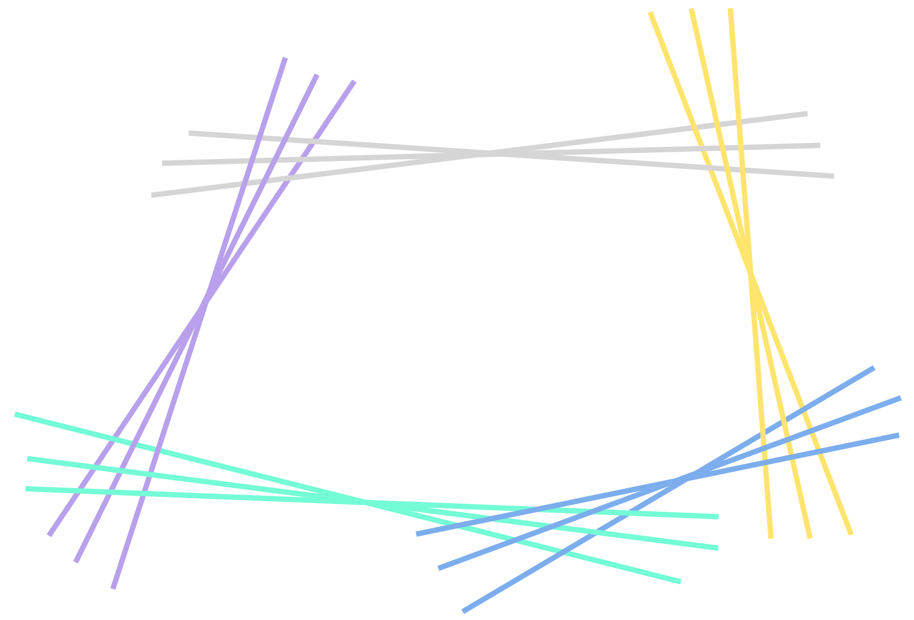
Online learning



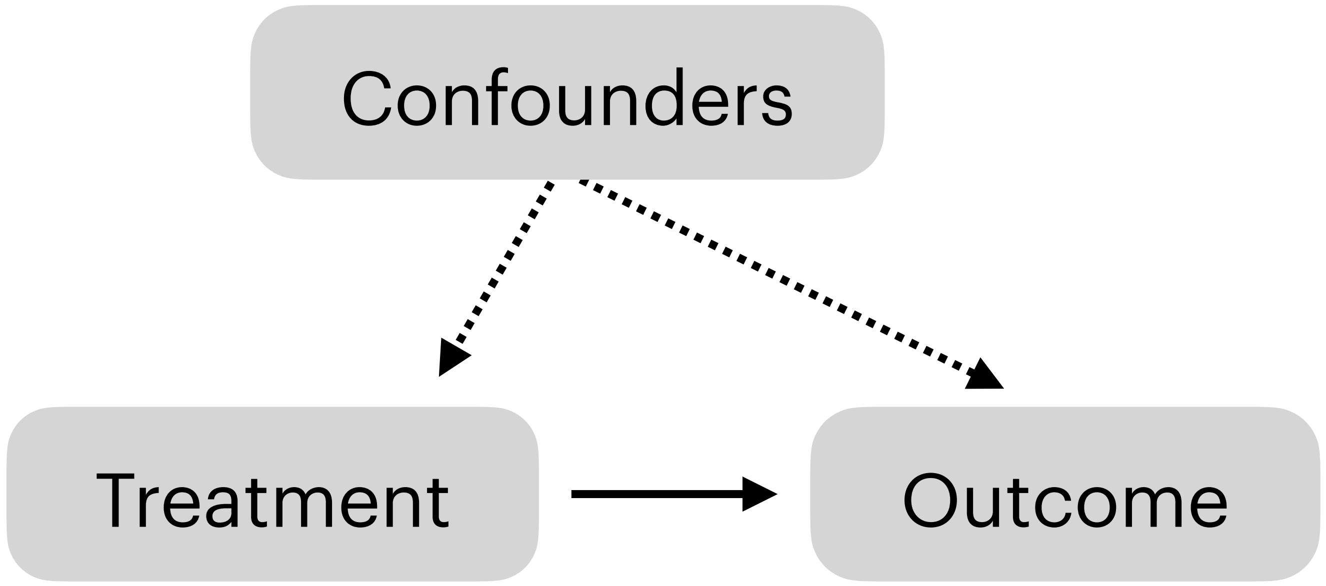
Reinforcement learning



Addressing uncertainty



Causal inference

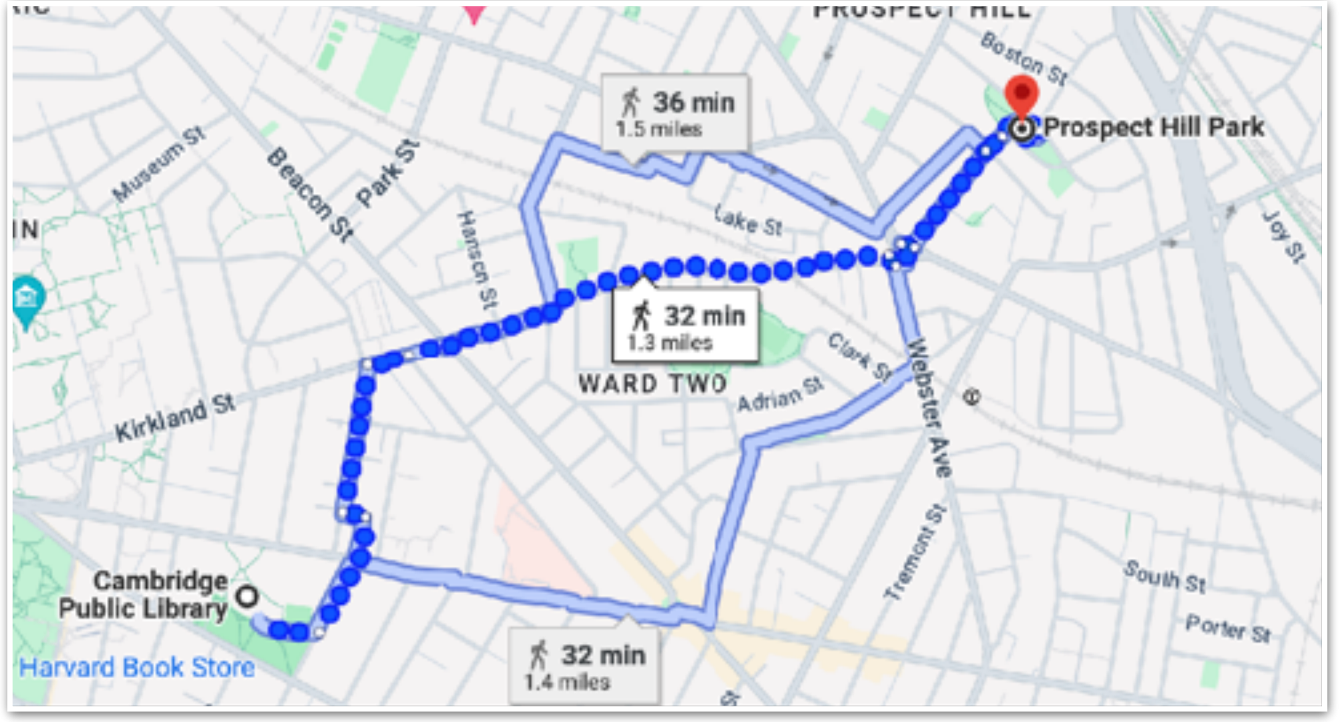


AI for conservation decisions

Optimization

Classic examples

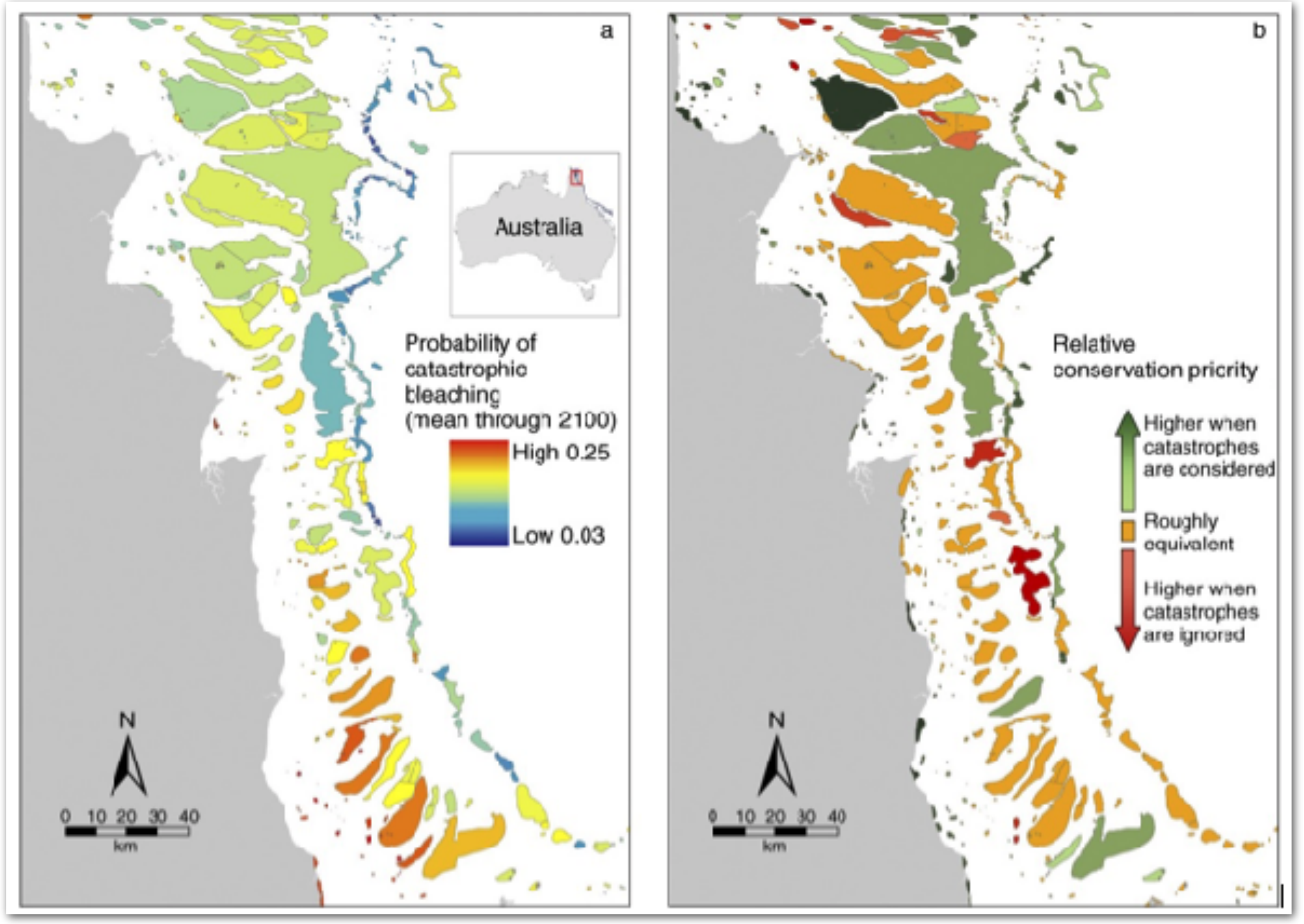
Google Maps routing



Air traffic control

Conservation examples

Prioritizing key land to conserve



Ball et al. (2009). Marxan and Relatives: Software for Spatial Conservation Prioritization

Optimization

Specifying a space of possible decision strategies and a performance measure to be maximized, then using computational methods to efficiency search the space.

$x_1, x_2, \ldots, x_n$ **decision variables** discrete or continuous
parameters of the model

max $f(x)$ **objective**
performance metric

subject to $h_n(x), g_n(x)$ **constraints** equality or inequality
limits on variables and their relationships

Optimization

$x_1, x_2, \ldots, x_n$ **decision variables** discrete or continuous
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limits on variables and their relationships

Foundation of machine learning algorithms *and decision-making more broadly*

Neural networks

Decision variables: Neural network weights

Objective: Maximize number of data points correctly labeled (classification)

Constraints: None

Land conservation

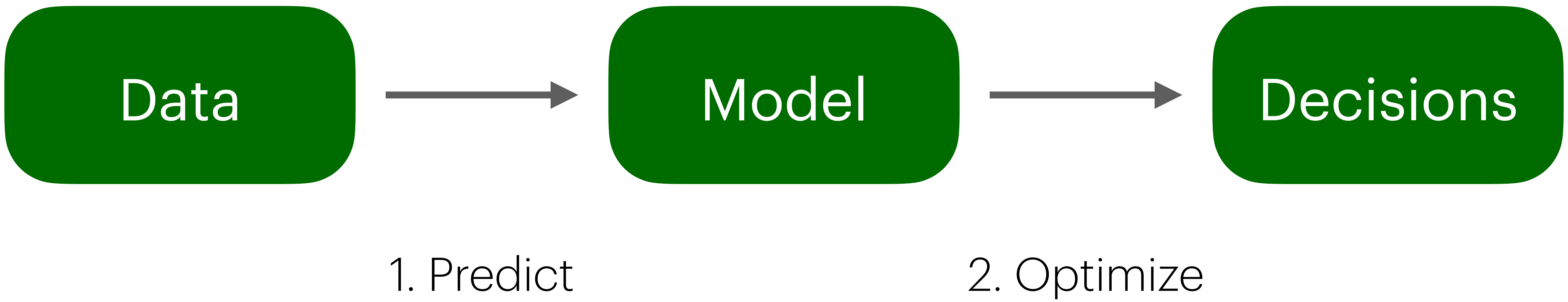
Decision variables: Whether to conserve specific parcels of land

Objective: Maximize habitat connectivity

Constraints: Spending budget

Optimization

Predict-then-optimize paradigm

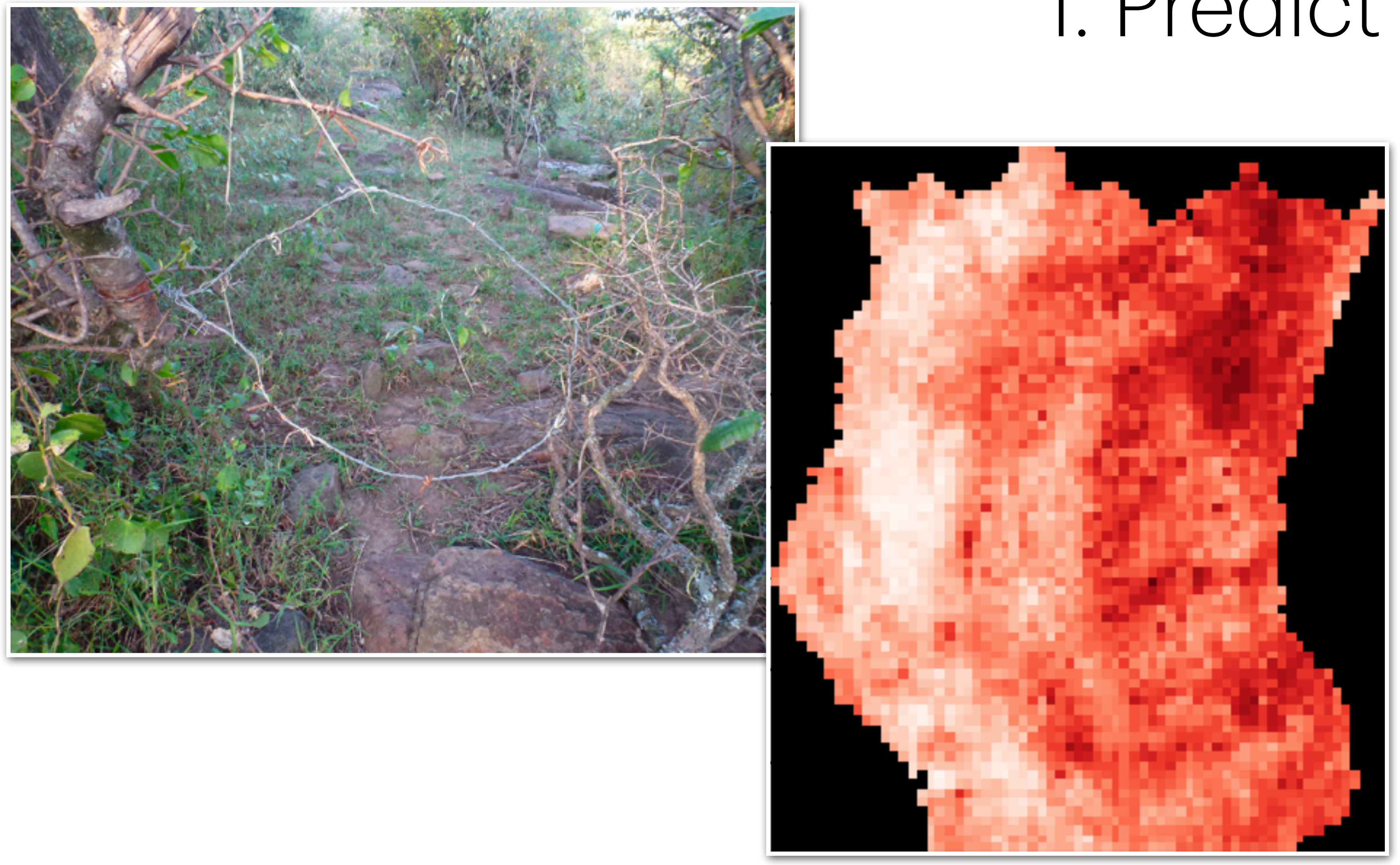


Optimization

Data → Model → Decisions

1. Predict

2. Optimize



Xu et al. (2020). Stay Ahead of Poachers: Illegal Wildlife Poaching Prediction and Patrol Planning Under Uncertainty with Field Test Evaluations. *ICDE*.

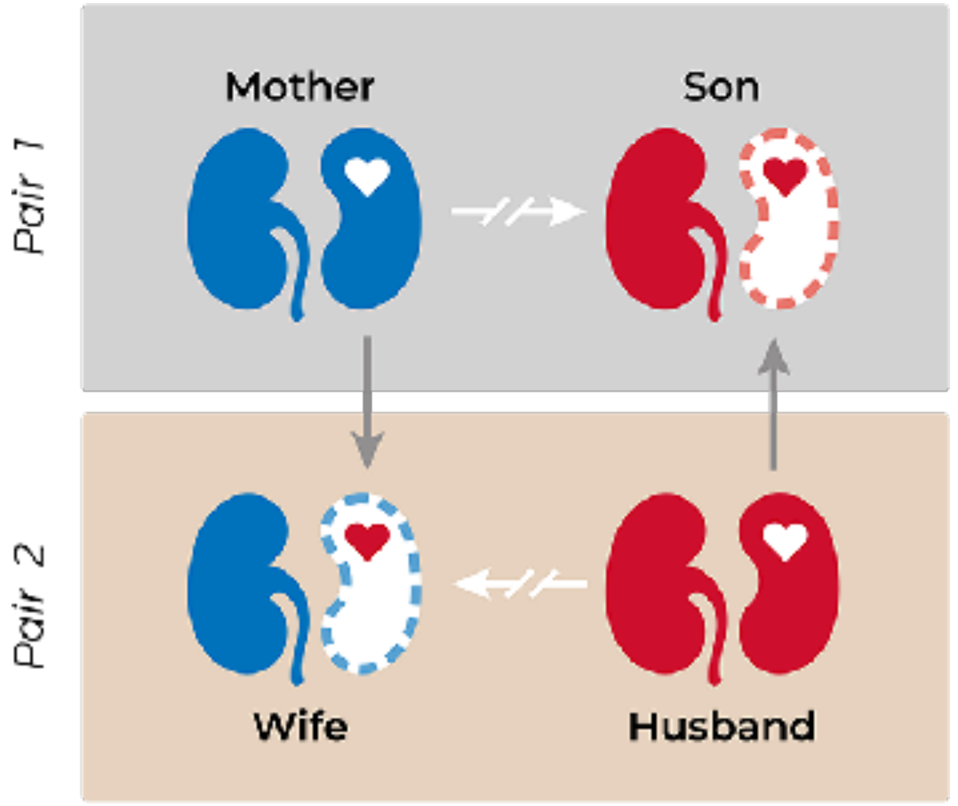
Market design

Classic examples

Rideshare: assign riders to drivers

DiDi Uber

Hospitals: assign kidney donors to patients



National Kidney Registry

Conservation examples

Payments for
ecosystem services

Photo: C. Carnemark / World Bank

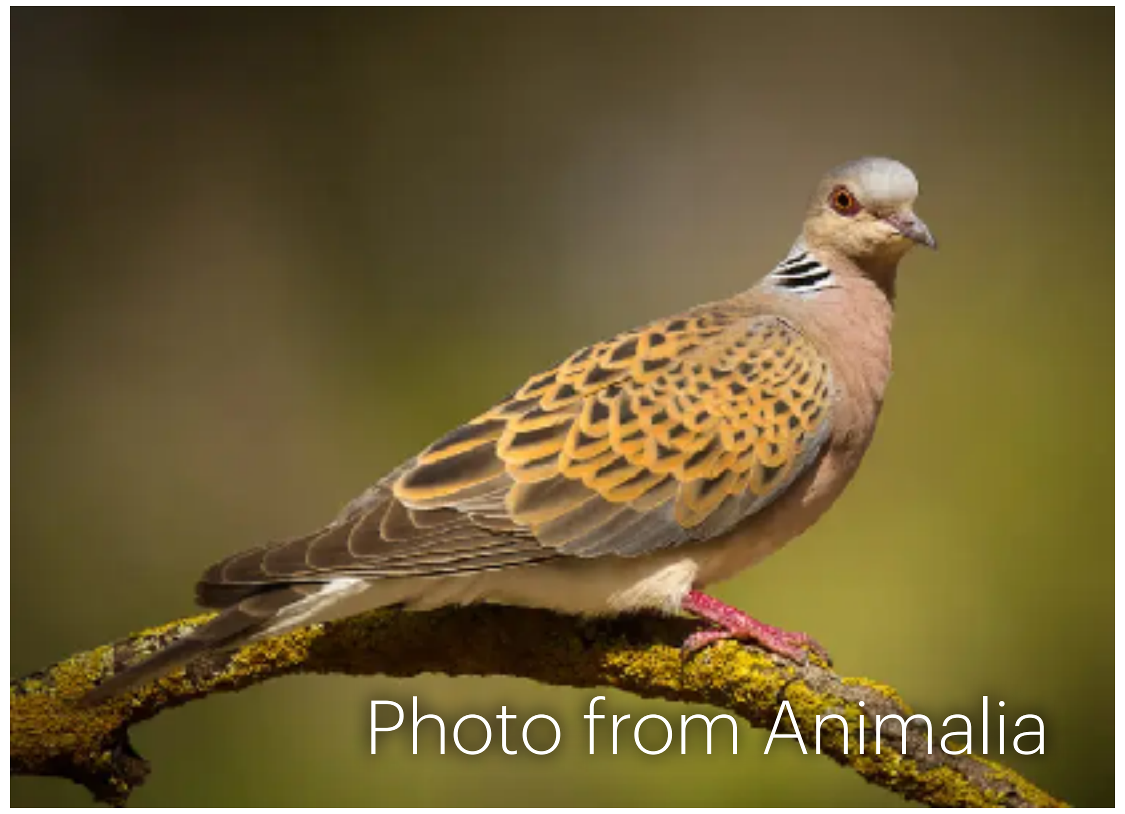


Photo from Animalia

Combinatorial auctions
for turtle dove habitats

The Economist

Market design

Payments for ecosystem services

ecosystem services water, carbon capture, habitat conservation, erosion management

compensation money / incentives

Market design

Conservation planning is challenging because of many distinct players who have their own incentives.

Especially in conservation, many benefits are *positive externalities* that aren't captured by any one individual.

e.g., ecosystem services

The goal of market design is to incentivize desirable behavior, and ensure the system is truthful and efficient.

Landowners

Industry

People far

Online learning

Classic examples

Email spam filtering

Recommender systems

Spotify tinder Google Ads

Conservation examples

Repeated patrol planning

Photo: Lily Xu

Xu et al. (2021). Dual-mandate patrols: Multi-armed bandits for green security games. *AAAI*.

Online learning

Learn models incrementally from data as new samples arrive

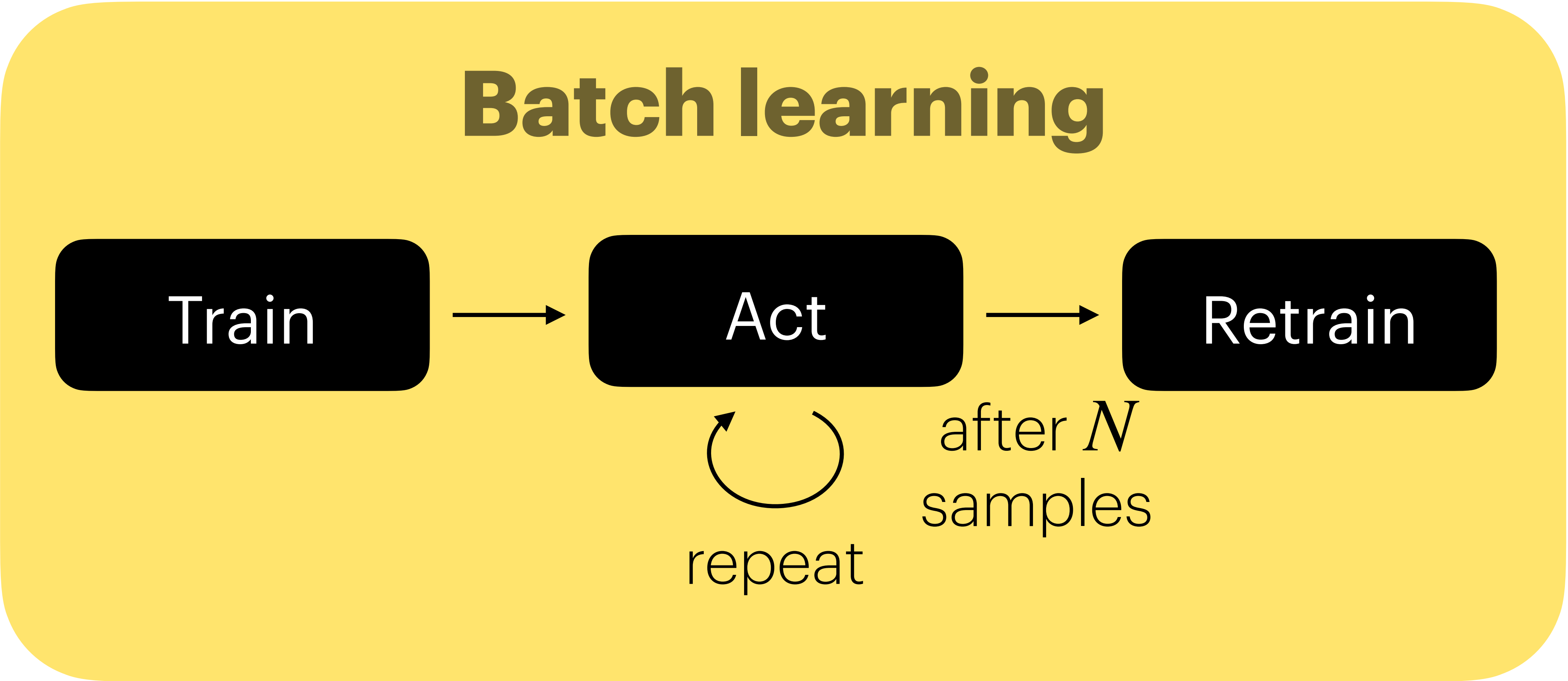
vs. "batch" learning

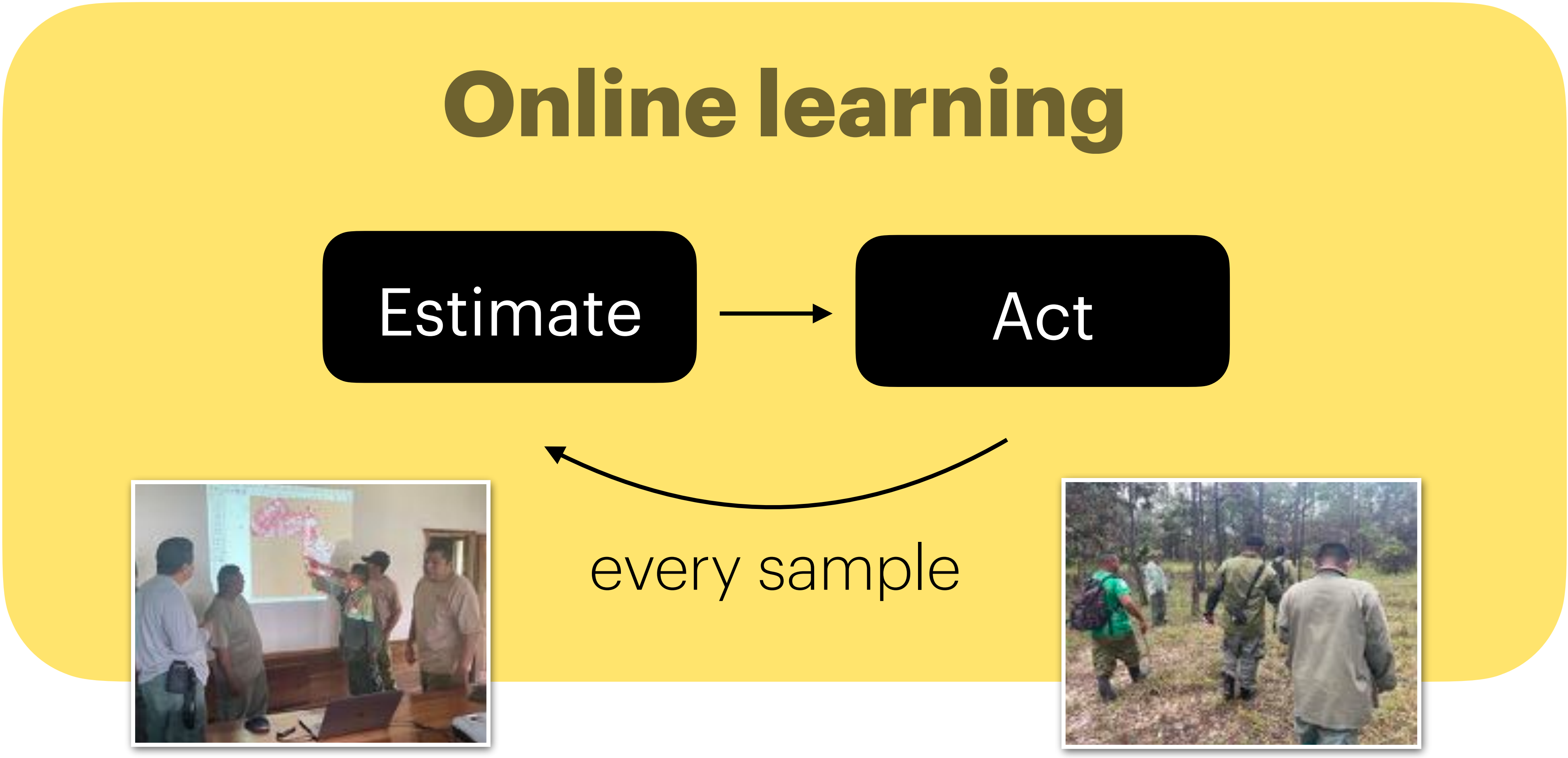
Useful when there is an action to be taken at repeated timesteps

Can be combined with human (expert) feedback

e.g., online active learning

Key methods: multi-armed bandits, unsupervised methods (online clustering, density estimation)





Reinforcement learning

Classic examples

Chess

Self-driving cars

Conservation examples

Fisheries management

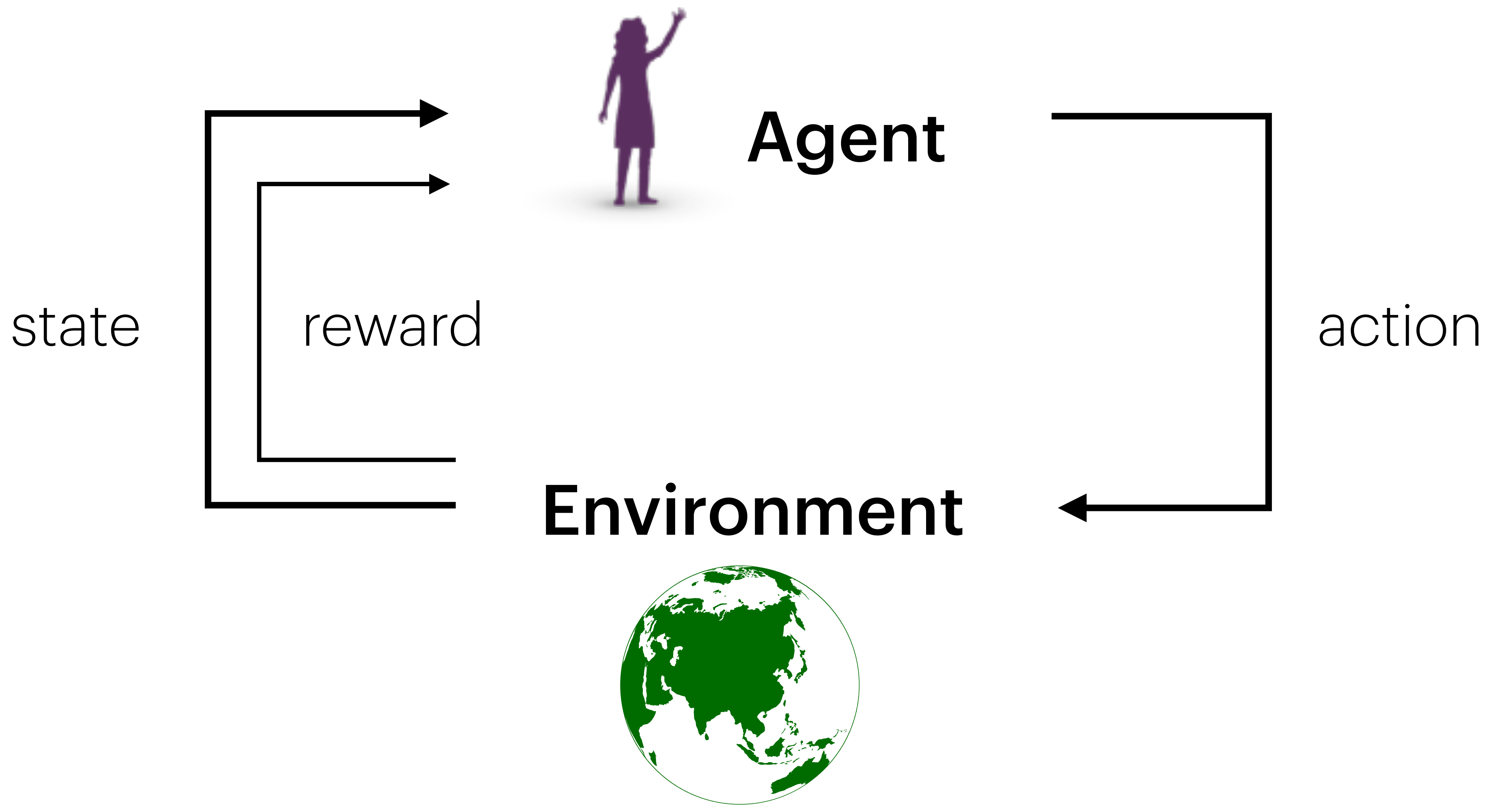
Precision agriculture

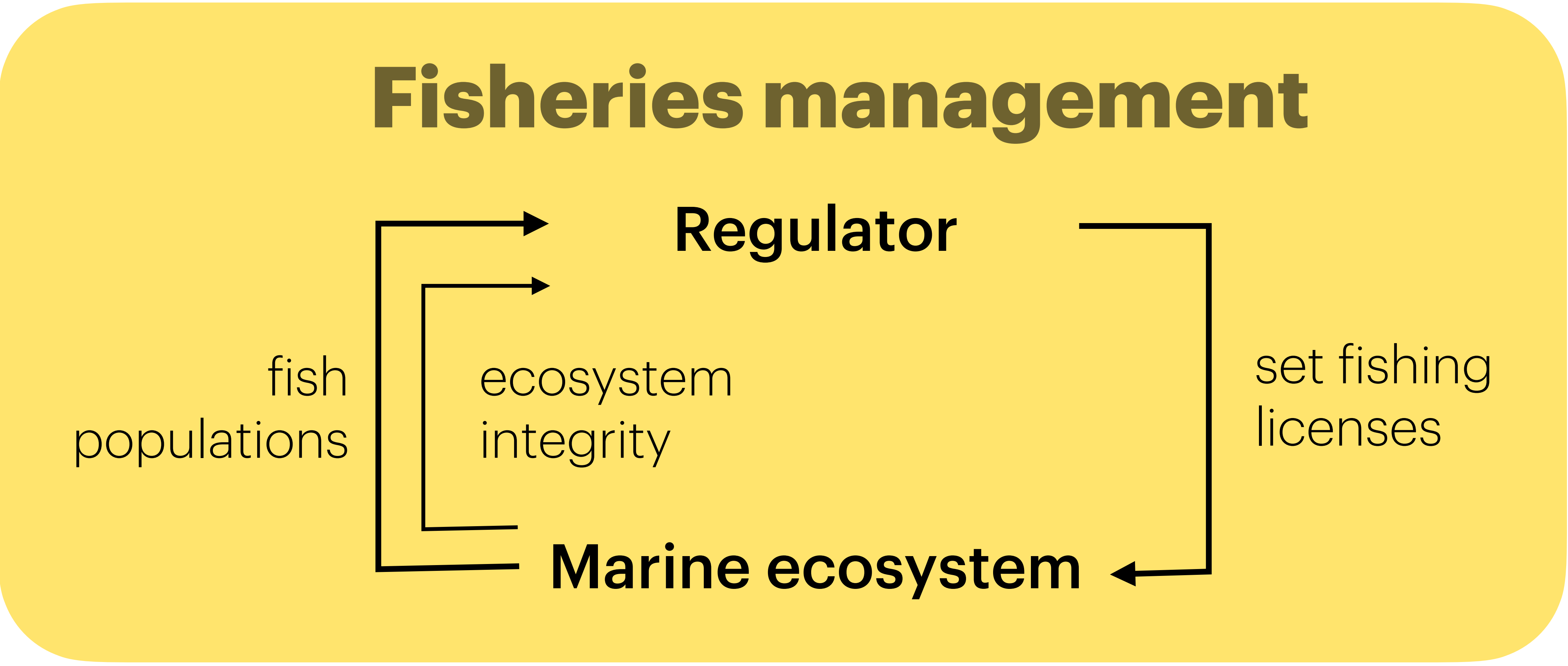
Reinforcement learning

Learning in real time through repeated interaction with the environment

or, often, a simulation of the environment

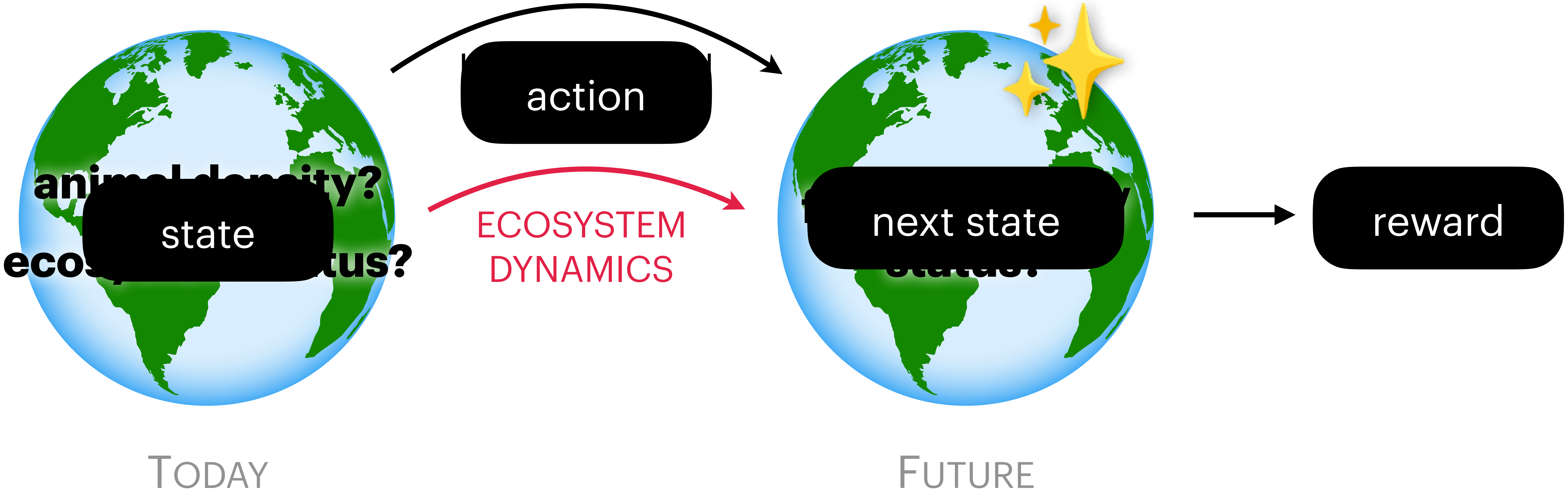
Sequential *nature is key:* Choice of action impacts both immediate success, and ability to learn about the environment to be exploited in future actions





Reinforcement learning

Sequential aspect is key



Markov decision process

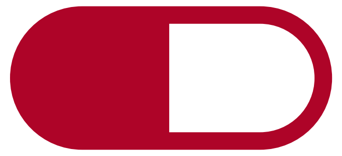
Question

What makes sequential decision-making particularly hard?

Causal inference

Classic examples

Medicine: Testing new drugs



New drug

Placebo

Education: Evaluating impact of class size

Photo: C. Sessums (Flickr)

Conservation examples

Randomized control trial of payments for ecosystem services (PES) in Uganda

Photo: IUCN

Jayachandran. (2017). Cash for carbon: A randomized trial of payments for ecosystem services to reduce deforestation. *Science*.

Causal inference

The study of cause-and-effect relationships

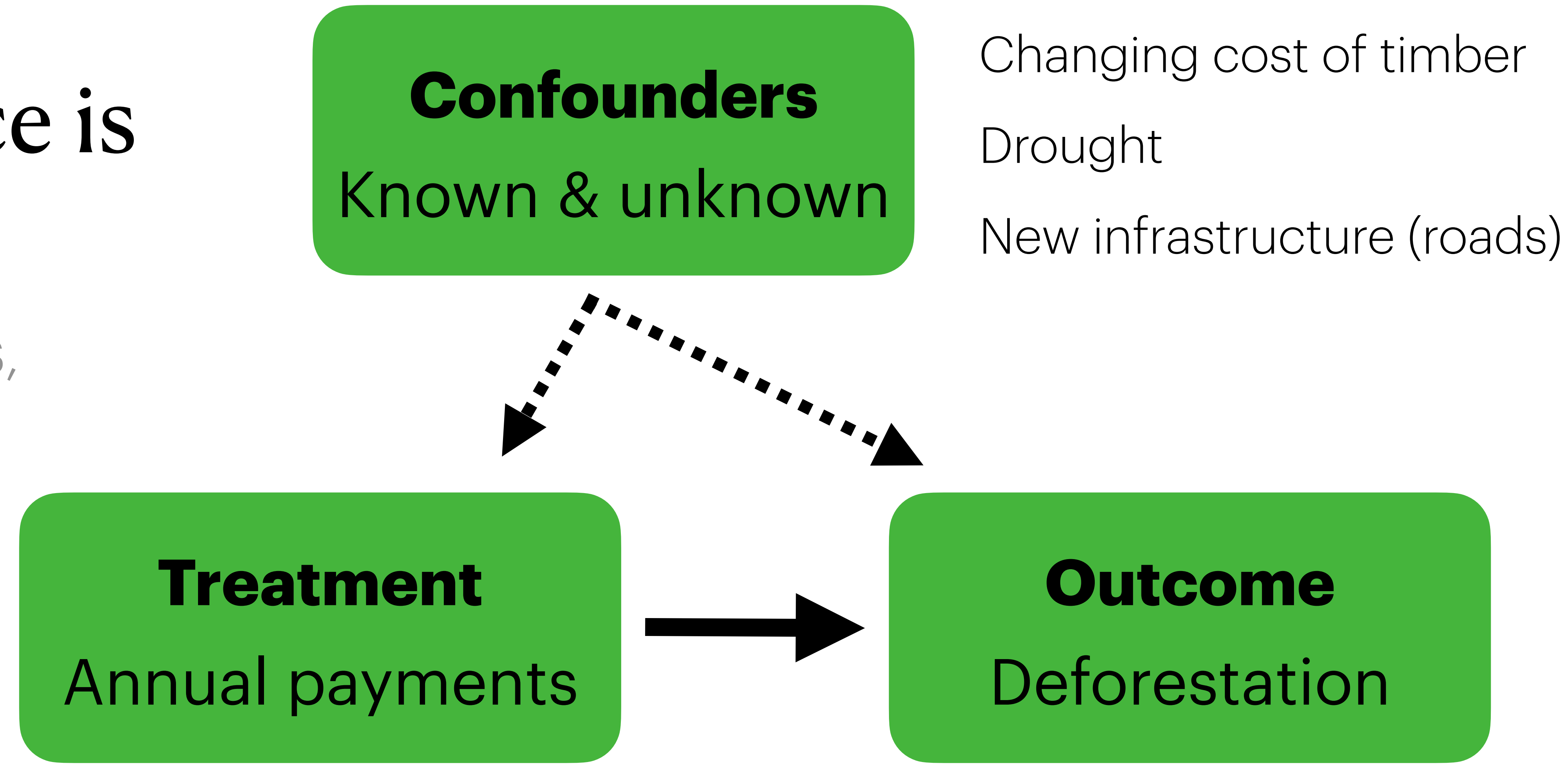
As we all know, correlation $\neq$ causation

Requires counterfactual reasoning

How much forest cover would there be if I didn't pay *this* landowner?

We can't duplicate the world, so causal inference is the art of estimating the counterfactual

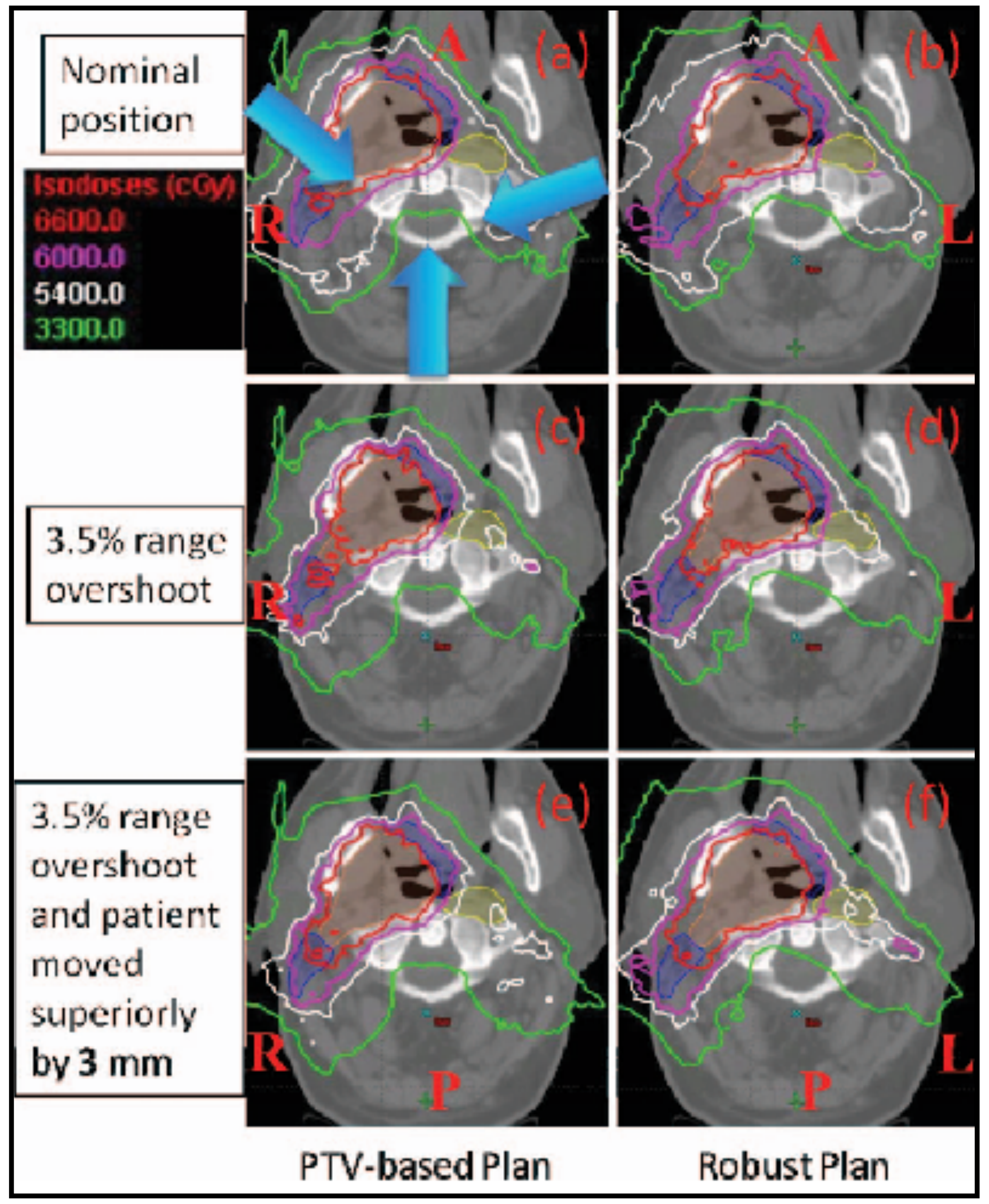
Through RCTs (randomized assignment), instrumental variables, regression discontinuity design, difference-in-differences, ...



Payments for ecosystem services

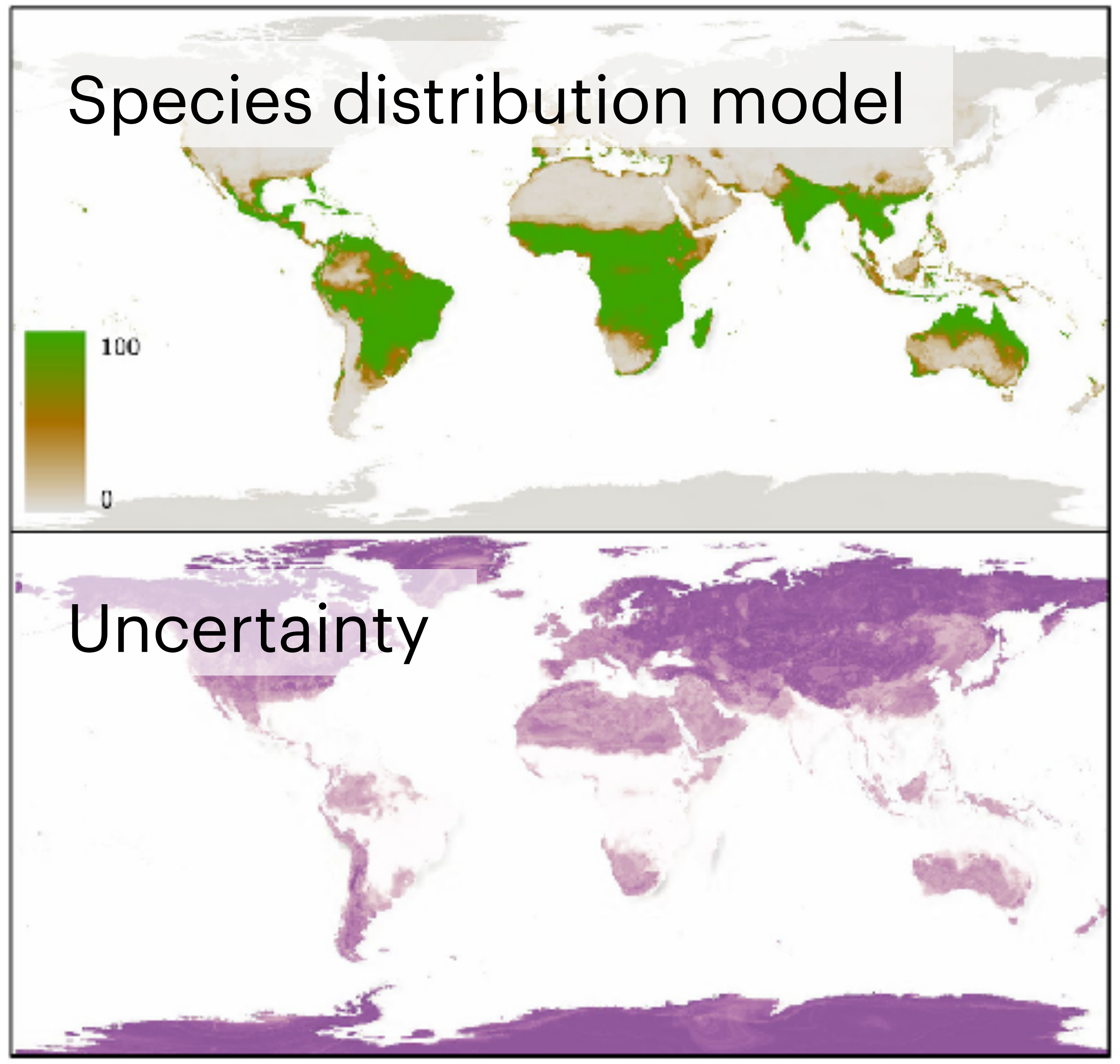
Addressing uncertainty

Classic examples



Chu et al. (2005). Robust optimization for intensity modulated radiation therapy treatment planning under uncertainty. *Phys Med Biol*.

Conservation examples

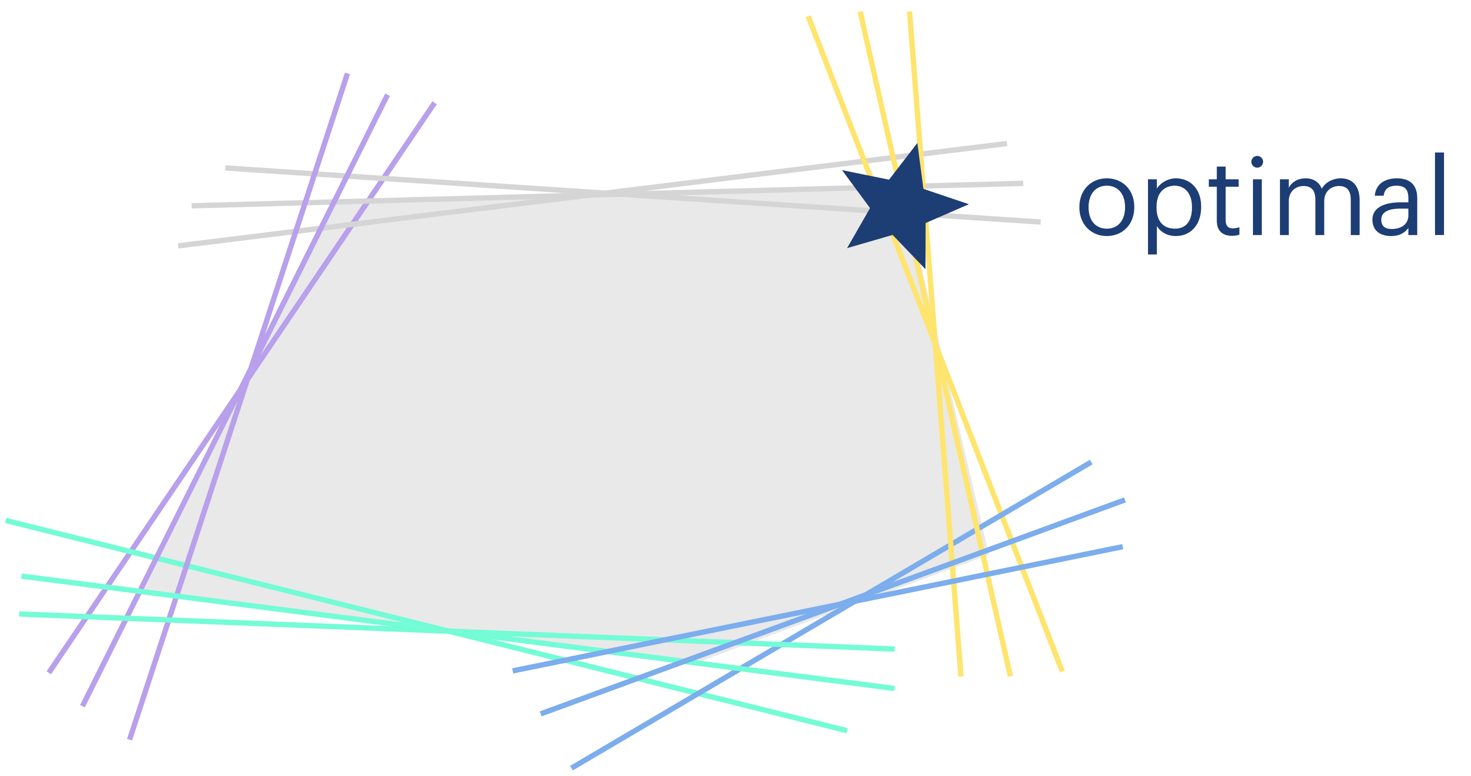


Niamir et al. (2019). Incorporating knowledge uncertainty into species distribution modelling. *Biodiversity and Conservation*.

Addressing uncertainty

Static setting: robust optimization

Habitat connectivity	$\max \ f(x)$?	Uncertainty in species distribution
Spending budget Protect at least 30% of jaguar habitat Preserve 500 km² Indigenous lands	subject to $h_n(x), g_n(x)$	Uncertainty in costs Uncertainty in habitat



Conclusions

Going deeper

Optimization

ML + optimization

Combinatorial optimization

Graph models

Market design

Game theory

Auctions

Online learning

Bayesian online learning

Adaptive learning

Reinforcement learning

Multi-agent planning

Sample complexity,
delayed feedback, ...

Addressing uncertainty

Uncertainty quantification

Robust planning

Partial observability

Causal inference

ML for causality

Ethical considerations

AI-based decision support tools are *aids*, not a replacement to humans

People working on ground have **expertise** — including cultural context and lived experience — that should be recognized and incorporated

Stakeholder involvement should be empowering, not exploitative

Recognize biases and harms in data & resulting decisions

Chapman et al. (2024). Biodiversity monitoring for a just planetary future. *Science*.

Conservation data justice: growing movement to recognize and overcome these biases

Pritchard et al. (2022). Data justice and biodiversity conservation. *Conservation Biology*.

AI for Conservation Decisions

Data → Model → Decisions → Evaluation

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I'm recruiting PhD students for Fall 2025 at Columbia!

Key methods

Optimization	Maximize a given objective under specified constraints
Market design	Incentivize desirable behavior
Online learning	Learn models incrementally from new data
Reinforcement learning	Learn through repeated interaction with the environment
Addressing uncertainty	Quantify and robustly plan around uncertainty
Causal inference	Study cause-and-effect relationships

Further readings

Overview to conservation decision making: Xu*, Rolf*, et al. (2023) Reflections from the Workshop on AI-Assisted Decision Making for Conservation. arXiv.

Biodiversity overview: UNEP. (2021). Nature for Climate Action Factsheet.

- Roe, Seddon, and Elliott. (2019). Biodiversity loss is a development issue: a rapid review of evidence. IIED Issue Paper.

Optimization: Beyer et al. (2016). Solving conservation planning problems with integer linear programming. *Ecological Modelling*.

Market design: Teytelboym. (2019). Natural capital market design. *Oxford Review of Economic Policy*.

Causal inference: Ferraro, Sanchirico, and Smith. (2018). Causal inference in coupled human and natural systems. *PNAS*.

Online learning: Hoi et al. (2021). Online Learning: A Comprehensive Survey. *Neurocomputing*.

Reinforcement learning: Zuccotto et al. (2024). Reinforcement learning applications in environmental sustainability: a review. Artificial Intelligence Review.

- Database: RL for Conservation gym

Uncertainty: Kochenderfer. (2015). Decision Making Under Uncertainty.

Relevant lectures and courses

Optimization: Geoff Gordon (CMU) optimization course (videos + slides)

Market design: Peter Cramton (Cologne) market design course (videos)

Causal inference: David Sontag (MIT) lecture (video)

Online learning: Shipra Agrawal (Columbia) lecture (video)
Alex Slivkins (Microsoft) multi-armed bandits course (slides)

Reinforcement learning: David Silver (UCL) RL course (videos + slides)

Uncertainty: Robust optimization playlist (videos)