Thesis proposal

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The proposal for my thesis, *Simulation models for predictive ecology*

Introduction

P1

Within the last several hundred years, human activity has rapidly changed Earth's atmosphere, oceans, and surface. Greenhouse gas emissions have caused an increase the temperature of both Earth's terrestial surface and its oceans, and both agricultural and urban development has rapidly reshaped the cover of Earth's surface. These the bulk of this change has occurred within the last several hundred years, a geological instant, potentially inducing shocks to ecosystems that could threated their integrity (**Scheffer?**). As a result understanding and predicting how ecosystems will change in the future, *ecological forecasting*, and making making descisions based on these predictions mitigating the consequences of this change, on ecosystems has emerged as an imperative for ecology and environmental science [Dietze (2017);].

P2

However, robust forecasting of ecological processes will change in the future is, to say the least, quite difficult (Beckage *et al.* 2011; Petchey *et al.* 2015). This difficultly is compounded by a few factors, the first being that sampling ecosystems is not easy. Ecological data is often biased, and noisey, spatially and temporally sparse. As a result *ecosystem monitoring* (Makiola *et al.* 2020) has emerged as an imperative. Developing a system for ecological observation, which is able to coordinate across locations. (**AndyUrbanBiomonitoring?** paper).

The second major challenge in forecasting ecosystems is that the underlying dynamics of most ecological processes are fundementally unknown (and unknowable) and instead must be inferred.

Much of the history of quantitatively modeling ecosystems have been done in the language of dynamical systems, describing how the value of an observable state of the system, represented by a vector of numbers $[x_1, x_2, ..., x_n]^T = \vec{x}$ changes as over time. It turns out to be much more effective to, rather than attempt to directly model $\vec{x}(t)$ itself, to instead describe how $\vec{x}$ changes from one timestep to the next, yielding models in the form of differential equations in continuous-time settings–$\frac{dx}{dt} = f(x)$– or difference equations in discrete-time settings–$x_t = f(x_{t-1})$–where $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is an arbitrary function describing how the system changes on a moment-to-moment basis (e.g. in the context of communities, f could be Lotka-Voltera, Holling-Type-III or DeAngelis-Beddington functional response). The form of this functional response in real systems is effectively unknown, and some forms are inherently more "forecastable" than others (Chen *et al.* 2019).

P3

However, we run into many problems when aiming to apply this type of model to empirical data in ecology.

The initial success of ODE models can be traced back to the larger program of ontological reductionism, which became the de facto apporoach model physical sciences after its early success in physics, which, and by the time ecology was becoming a quantitative science (sometime in the 20th century, depending on who you ask), became the foundation for early quantitative models in ecology.

But ecosystems are perhaps the quintessential example of system that cannot be understood simply by iterative reduction of its components. Emergent phenomena, mechanisms at different scales, etc.

Some have been explored in the ecological literature: (1) Some applications of dynamic models in ecology assume long-run equilibrium. (2) Stochasticity

(3) Ecological processes vary across more variables than the tools of analytic models are suited for. As the number of variables in an analytic model increases, so does the ability of the scientist to decern clear relationships between them, and so does overfitting potential. Curse of dimensionality— Until the 20th century, no theory of the gravitational dynamics of more than 2 bodies. Understanding the gravitational dynamics of more than two planets with any reliability proved difficult. Using the same models (diffeqs), how could we adequately predict ecosystems?

P4

The term *ecological forecasting* implicitly creates an analogy between predicting how ecosystems will change in the future by using the term "forecasting"—the most immediate analog being the success story of weather forecasting via numerical weather prediction (NWP).

Although it is become almost hack to complain about the dang weather forecast being wrong, over the least 50 years the (Bauer *et al.* 2015).

The success of NWP, and the Earth observations that support it should serve as a template for development of a system for monitoring Earth's biodiversity. Much like ecology, NWP is faced with high-dimensional systems that are governed by different mechanisms at different scales.

NWP has worked because it incorporates information about data and meteorological processes collected at difference scales into models that. Use of computational methods in NWP.

Much as one would not aim to forecast the weather in Quebec by applying Navier-Stokes, forecasting ecological systems must

Transition to simulation as the solution: shift toward approach of building models that *generate* data.

(resolving the semantic ambuity of what differentiates "mechanistic" vs "phenomological" models is out of scope for now).

More broadly a reflection reflect ecology lagging behind the statistical methods used in sciences that face similar challenges (many dimensions, many mechanisms at different scales, each with stochasticity). Chaotic dynamics emerge from simple analytic models, and . Whether ecosystems actually exhibit chaotic behavior is a different question.

P5

But forecasting isn't the only difficult problem here.

Transition to theme of optimization given unknown information. A forecast gives us a range of future values with uncertainty around them. Further a convenient property that a forecasting model's uncertainty goes up over time (if we assume the underlying process is Markov–this is a strong assumption but oft true of the models we fit to temporal data)

In face of uncertainty, decision making is an optimization problem. We have some goal state for the future, and some estimate of what the state of the world will be given a set of actions. Frame optimization problem mathematically an introduce concept of solution-space and constraint.

Indeed Marx's most well known quote that "philosophers have hitherto only interpreted the world in various ways; the point is to change it." and a necessary step toward establishing a just and sustainable world.

[Figure 1 about here.]

P6 – final intro para

Three major components here: 1) Ecosystem monitoring, 2) Forecasting using the products of that monitoring, and 3) Choosing the best possible mitigation strategy.

This flow is outlined in the left panel of fig. 1

Chapter One: Forecasting the spatial uncoupling of a plant-pollinator network

Plants and pollinators form interaction networks, called the "architecture of biodiversity" (**Jordano2007?**).

The stability, function, and persistance of ecosystems relies on the structure of these interactions. Antropogenic change threatens to unravel these networks. Two aspects to this change: spatial and temporal. Spatially, range shifts along elevational gradient, and temporall, phenological shifts.

The issue is that we don't really know what interactions are like now. So not only do we need to predict with data that is spatially and temporally sparse and likely to contain many interaction "false-negatives" (**Strydom2021?**)

This chapter uses several years of data on bee-flower phenology and interactions, combined with spatial records of species occurrence via GBIF, to forecast how much overlap there will be between plants/pollinators in space/time.

In stages, (1) take data from multiple sites to predict a spatial metaweb of *Bombus*-flower interactions across Colorado. (2) Predict how these spatial distributions will change under CMIP6. and (3) quantify the lack of overlap between species for which there is a predicted

CH1 concept figure

Data

The data for this chapter is derived from multiple souces and can be split into three categories. (1) Field data from three different locations acvross Colorado. All field sites have multiple plots across an elevational gradient.

System description: lots of data on *Bombus* (bumblebees) and wildflowers. Three different sites, (7/7/3) years each, each covering an elevational gradient.

Methods

Split the process into parts.

1) Building an interaction prediction model. 2) Make it spatial based on distributions. 3) Forecast distributions based on CMIP6.

Preliminary Results

1) we got a tree

Transition to next chapter by discussing uncertainty in interaction prediction across space.

Chapter Two: Optimizing spatial sampling of species interactions

There are false-negatives in interation data. Co-occurrence is not the same thing as interaction (**cite?**), but often is used as a proxy.

This chapter unravels the relationship between a given species relative abundance and the sampling effort needed to adequately understand this species distribution and interactions.

There is more than one way to observe a false-negative.

[Figure 2 about here.]

Methods

- the missing link paper, turn this into optimizing with two different SDMs relative abundance and its effect on false negative non-independent associations in samples
- simulate species distribution and efficacy of detection given a set of observation points where the dist from observation site decays. optimize set of repeated sampling locations L for a *known* distribution D. address SDM not being the territory

Results

- nonrandom association figure sampling effort under neutral model

In-progress results

CH3 optimizing corridor placement

This chapter proposes an algorithm for optimizing restoration across space (corridorplacement/restoration effort) given a raster where each cell indicates land-cover. The optimization method uses the result of a simulated process (specifically occupancy dynamics in the landscape) and uses simulated annealing to estimate the global optimum of the targetstate (specfically mean-time-to-extinction for the occupancy dynamics example).

Methods

- land cover -> resistance -> extinction time simulated annealing to
- optimize landscape optimization

CH4 a software note on the resulting packages.

(MetacommunityDynamics.jl: a virtual laboratory for community ecology): a collection of modules in the Julia language for different aspects of metacommunity ecology, including most of the code used for the preceding chapters.

- TK conceptual figure with interfaces between what I'm writing / have
- contributed to and linked with other libraries
- `Observatories.jl`, `Corridors.jl`, `MCD.jl`

Conclusion

Appendix

[Figure 3 about here.]

References

Bauer, P., Thorpe, A. & Brunet, G. (2015). The quiet revolution of numerical weather prediction. *Nature*, 525, 47–56.

Beckage, B., Gross, L.J. & Kauffman, S. (2011). The limits to prediction in ecological systems. *Ecosphere*, 2, art125.

Chen, Y., Angulo, M.T. & Liu, Y.-Y. (2019). Revealing Complex Ecological Dynamics via Symbolic Regression. *BioEssays*, 41, 1900069.

Dietze, M.C. (2017). Prediction in ecology: A first-principles framework. *Ecological Applications*, 27, 2048–2060.

Makiola, A., Compson, Z.G., Baird, D.J., Barnes, M.A., Boerlijst, S.P., Bouchez, A., *et al.* (2020). Key Questions for Next-Generation Biomonitoring. *Frontiers in Environmental Science*, 7.

Petchey, O.L., Pontarp, M., Massie, T.M., Kéfi, S., Ozgul, A., Weilenmann, M., *et al.* (2015). The ecological forecast horizon, and examples of its uses and determinants. *Ecology Letters*, 18, 597–611.

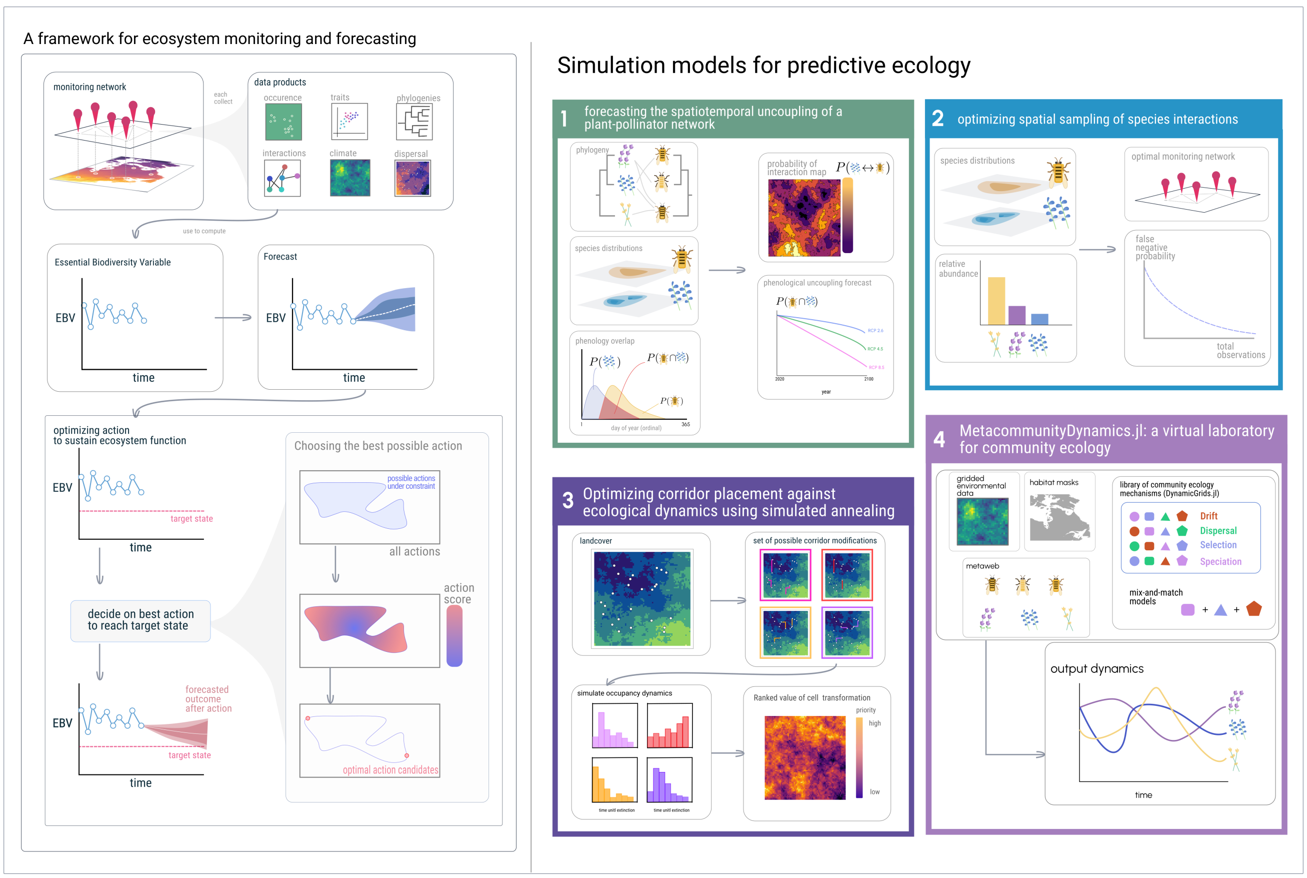

Figure 1: thesis concept

./figures/ch2.png

Figure 2: taxonomy of false negatives

./figures/trees.png

Figure 3: trees