Novel Mathematical and Statistical Approaches to predicting Species' Movement under Climate Change (19frg248)

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1 Overview of the Field

Climate change and habitat loss are two of the primary causes of global biodiversity loss [17, 20]. Areas where a species lives - the geographic range - become gradually unsuitable as the climate changes from that which the species can tolerate to levels of temperature, rainfall, and related variables that no longer support its populations. Under a changing climate, species must "adapt, move or die" [7]. Here, we consider moving or dying.

Populations need to shift - generally polewards - to track their suitable climate as it shifts. This process is captured by the concept of the velocity of climate change [14, 8]. Based on climate change and the factors that determine its realization in space - location on the globe, local topography, etc - the velocity of climate change represents the rate at which a population must shift to remain in the same climate space over time.

Estimated poleward speeds, based on predicted temperature changes by the end of this century, range from 0.08 to 1.26 km yr^{-1} depending on the geographic region [14]. If a species can shift populations at a speed at or above the local velocity of climate change, it has the potential to persist; if it cannot, it is more likely to go extinct.

Habitat loss is the other major cause of biodiversity declines. Globally, 75% of the land surface has been converted by humans [11]. The precise consequences of habitat loss can be considered in terms of the critical patch size. As the area of available habitat declines, the population loses more dispersers beyond the patch edge. At a critical patch size the rate of population growth is not sufficient to counter the loss of dispersers, and the population goes extinct [22, 12]. Thus, species with a lower population growth rate or further dispersal will go extinct sooner as habitat shrinks.

The mathematical literature has explored the invasion and persistence thresholds for species whose habitats shift at a constant speed (e.g., [19, 2, 24, 10, 13, 18]) as extensions of the critical patch size problem for populations diffusing out of a favorable habitat [15]. These studies, based on analyses of models formulated as partial differential equations or integrodifference equations, have helped us to identify some of the species and habitat characteristics that facilitate persistence. In particular, these studies establish a connection between a species' spreading speed (i.e., the rate a population spreads into an empty habitat of infinite extent), its thermal tolerance (which determines the extent of the suitable habitat) and climate velocity (which determines how fast the habitat is shifting).

To apply these models to a particular species, we must estimate the model's parameters from data. Roughly speaking, these data fall in two categories: demographic data and dispersal data. For plants and animals, demographic data, in the form of population projection matrices, have been collected in repositories. For example, matrices for 695 plant species have been assembled in the COMPADRE database [21]. Empirical approaches to measure species' movement, such as the use of molecular markers and GPS tracking, have advanced enormously [6]. These advances are producing an increasing amount of dispersal data, some of which has been gathered together and is available (see, [4]).

2 Recent Developments and Open Problems

While demographic and dispersal data are increasing, these data remain sparse as they are intensive to collect. For example, there are approximately 391,000 known vascular plant species on Earth [16], and autecological studies to estimate population spread for each are not feasible. Hence, most fundamental research on population dynamics and spread has focused on a few well-parameterized case studies. Projections of population spread in response to climate change have been done for a limited number of species [3, 5]. Nevertheless, the development of risk criteria that can be applied to a wide range of species by conservationists is highly desirable. This will require effectively synthesizing data with mathematical models; challenges to which include simplifying often complex data with minimal loss of information and handling sparsity in data as the size and complexity of data increases. Management decisions for species will require projections of population spread based on realistic demographic and dispersal scenarios that can be generalized to a range of species.

Our objective is to develop mathematical and statistical approaches that take advantage of the increasing amount of biological data to predict invasion and persistence of species in a changing world. In this Focussed Research Group, we aimed to:

1. determine if there is a direct way of going from variability in the input parameters to an estimate of what fraction of species can keep up with climate change.

2. develop a new generation of mechanistic models for growth, survival, fecundity, and dispersal in response to changing temperatures and analyse these models mathematically using methods from traveling wave theory and spreading speeds to examine how changes in temperature will influence invasion/persistence as climate change alters demography and dispersal.

3 Scientific Progress Made

For **Objective 1**, we developed general mathematical insights on the distribution of spread speeds depending on the distribution of dispersal and demography and their covariation using integrodifference equations (IDEs) and assuming dispersal is normally distributed. In this model there are two random variables, the arithmetic growth rate R and the dispersal coefficient D. We derived the distribution of spreading speeds $\left(C^* = 2\sqrt{RD}\right)$ when each of these parameters was fixed and the other was varying according to an exponential, lognormal, or gamma distribution. We also examined the distribution of spreading speeds when both varied independently assuming both had the same distribution (i.e., exponential, lognormal, and gamma). We then explored the distribution of spreading speeds when R and D are correlated for bivariate lognormal and bivariate gamma distributions. Finally, we considered the distribution of critical patch size $\left(L^* = \pi\sqrt{\frac{D}{R}}\right)$ using the ratio distribution of a bivariate lognormal. Using these mathematical results, we will predict the global distribution of species vulnerabilities to habitat loss and climate change based on global databases. From this, we can estimate the proportion of species that may be at risk to either habitat loss or climate change based on estimates of climate velocity from the literature (e.g. [14]). We will also examine how correlation in dispersal and demography (e.g. dispersal syndromes, [1]) influence critical patch size and spread rates.

For **Objective 2**, we developed specific approaches for incorporating temperature responses of demography and dispersal into mechanistic models. We began with a McKendrick Von Foerster model and then moved to an integrodifference equation with stage-structure. We used ragweed (*Ambrosia artemisiifolia*) as an empirical example. The distribution and shift of populations over space of ragweed is of interest to many people due to its role as an allergen. Much is known about its dispersal and demography, but understanding how increasing temperature will affect dispersal and demography, and therefore the spread and shift in populations is less studied. We decided to examine five different cases of temperature fluctuations within the year: 1) constant, 2) stochastic, 3) periodic, 4) increasing trend, and 5) periodic with increasing trend. We assume that demography (i.e., survival, growth, and reproduction) responds to temperature according to a β distribution. We assumed a Laplace distribution for dispersal and that mean dispersal distance increases with the size of reproductive adults. This model could be expanded to investigate spread across a landscape that varies geographically in temperature as well as including density-dependence in plant performance.

4 Outcome of the Meeting

We made significant progress on both our objectives and identified several immediate next steps that will result in various products. Results for **Objective 1** will be finalized by participants and a manuscript is in progress that will be submitted within six months. Zhou will lead a project extending the results derived in this meeting to moving habitat models. Participants will gather at the National Institute for Mathematical and Biological Synthesis (NIMBioS) in Spring 2020 to work on this project. Other extensions to the results of **Objective 1** we discussed are 1) examining the distribution of wave speeds when including stage structure and 2) developing similar theory for the furthest forward velocity from a branching process. Initial models that emerged from **Objective 2** will be further developed, analyzed, and parameterized by Bogen and Beckman with data provided by Bullock. We also identified new directions of this work.

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