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Modeling Responses of American Ginseng (*Panax quinquefolius* L.) Populations to Different Levels of Simulated Harvest

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Abstract

Wild-harvested American ginseng (*Panax quinquefolius* L.) is traded internationally for its medicinal properties, and North Carolina is one of the United States' leading exporters of wild American ginseng. Harvest is regulated by state, and states must demonstrate that harvest is not detrimental to ginseng's long-term viability, so to determine if North Carolina regulations adequately protect ginseng, the demographic characteristics of five local populations were examined. Annual censuses were conducted for 2 years, tracking individual plants and recording leaf number and flower presence or absence. In the second year, data on each plant's fruit production were collected, and seed production was estimated using a published value of average seeds per fruit. Demographic data were used to construct a population matrix model for each population, and growth rate (with 95% confidence intervals), stable size distribution, and the elasticity of growth rate to transition probabilities were calculated. Three of the five populations were declining in the absence of any harvest, so for these populations, times to extinction were projected. The effects of increasing harvest rates (up to 100% of legally harvestable individuals) on growth rate were projected for the other two populations. The SC population was most resilient to harvest, with a growth rate of 1.18, while the MP population was more vulnerable. There was no clear distinction between growing and declining populations in either stable size distribution or elasticity of growth rate to transition probabilities. Sampling will continue so that in several more years, a more robust data set can be used to provide more reliable conclusions.

1. Introduction

American ginseng (*Panax quinquefolius* L.) is highly valued in East Asia for its medicinal properties. While it is grown commercially in the United States, traditional Chinese medicine maintains that wild-harvested ginseng is medicinally superior to its cultivated counterpart, thus the demand for wild ginseng remains high[1]. Ginseng is an herbaceous perennial; the aerial stem is born from a perennating rhizome, which is attached to a large taproot[2,3]. Ginseng is also long-lived (50+ years), making populations particularly vulnerable to harvesters, who remove the medicinal rhizome and root, killing the plant. Each year, American ginseng produces 1-4 leaves, called prongs. Larger plants have a greater survival rate in the absence of harvest and produce more seeds than younger plants. Two-prong plants will occasionally produce seeds (2.0 ± 0.7 /plant), but the great majority of seed production occurs in three-prong (5.1 ± 2.1 /plant) and four-prong (12.0 ± 2.7 /plant)[2] plants. While American ginseng is widespread throughout eastern North America, it is sparsely distributed and not abundant in any portion of its range[4]. Wild *P. quinquefolius* is listed as endangered or threatened in 5 states, and harvest is regulated in twenty-four states. These states must report annually to the U.S. Fish and Wildlife Service to demonstrate that harvest does not affect populations' long-term viability [1,5]. However, studies of phenology, demographics, and genetics suggest most states do not impose regulations strictly enough to ensure the survival of wild populations. Harvest seasons begin too early in most states to allow fruits to mature[5] and Van der Voort and McGraw found that West Virginia harvest regulations were not sufficient to protect local populations[6]. In a study simulating random legal harvesting of plants, Cruse-Sanders et al. recommend a harvest level of less than 16% to preserve populations' genetic diversity[7]. Both allelic richness and expected heterozygosity decreased significantly with increased harvest. A number of studies have been conducted in southern Québec and West Virginia to estimate sustainable harvest limits. In Québec, Charron and Gagnon calculated sustainable harvesting levels of up to 16% of 3-4 prong plants harvested per year[16]; and in West Virginia, populations can withstand harvesting of up to 25%, provided seeds are buried and harvest is delayed until the fruits are mature[6,20].

These are informative results, but their application to North Carolina populations may be limited. Southern Québec is at the extreme northern end of ginseng's range, so populations are generally smaller and individuals experience a shorter growing season (consecutive days where temperature is above 0°C) [16]. In western North Carolina, the average growing season ranges from 196 (Asheville, 680m) to 153 days (Coweeta Experimental Station, 680 m elevation)[21], while the growing season in Morgantown, WV averages 161 days (Morgantown Lock and Dam, 215 m elevation)[21]. The overabundance of white-tailed deer in West Virginia also affects ginseng population dynamics[20,22], primarily by browsing large reproductive plants before seed production. However, in North Carolina, white-tailed deer herds are much smaller[23] and likely exert much less pressure on ginseng populations. There is also evidence for a genetic difference between populations in the southern Appalachians and more northern populations. Populations in the southeast U.S. have been found to be more genetically diverse, supporting the hypothesis that the southern Appalachians provided a refuge for species during Pleistocene glacial periods[25].

I used population matrix modeling[9,10] to estimate sustainable harvest limits and determine if current regulations adequately protect five local populations of wild ginseng. Population matrix modeling is a relatively simple and accurate way to study populations of species with several distinct life stages[10], in which populations are broken up into mutually exclusive classes based on age, size, or stage of development. A model is constructed by estimating transition parameters for each class. Parameters are identified by an ordered pair, where each parameter with ordered pair (i, j) is the probability that an individual in class i will be in class j in the next year. All parameters are between 0 and 1, except the fecundity parameters, which give the average number of seeds produced per individual in each class. This is the most common method for modeling ginseng populations[6,16,17], and more generally for conducting population viability analyses on a wide variety of species[11-15], including other perennial herbs (*Nardostachys grandiflora* DC. (Spikenard)[14], *Cirsium palustre* L. (Marsh Thistle)[16], *Primula veris* L. (Cowslip)[16]). The aim of my research was to contribute new information to the overall body of knowledge regarding ginseng harvest, because the demographics of American ginseng populations in the southern Appalachians had not been studied. This research was part of a collaboration with other undergraduate research students studying the genetics and physiology of *P. quinquefolius* to provide a more complete characterization of local populations. Regulations on North Carolina private and public land restrict harvest to 3- and 4-prong plants, and require harvesters to plant the seeds of collected plants. The legal harvest season is from September 1 to December 31[26]. The U.S. Forest Service (USFS) has a stricter set of regulations. On USFS land, harvest season is from September 1 to September 30, and harvesters must buy a permit for $40 per wet pound. Harvest is limited to 3 wet pounds per person per year[27]. In my research, I will try to answer the following questions: are there any demographic similarities among growing and/or declining populations, and what is the maximum sustainable harvest level for each population?

2. Methods

2.1. Study Sites and Censuses

We monitored 5 populations in western North Carolina. Three populations (PC, SC, LB) were within several miles of each other, while the other two were in different counties (MP, MC). For conservation reasons, no further information is provided about study sites' locations.

Ginseng populations were censused once over the summer of 2011 (May 18 - July 21), and twice over the summer of 2012 (June 29 – July 23; August 6 – August 17). In the June/July census, presence or absence of an inflorescence and number of leaves were recorded. Fruit number was recorded in the August census, which took place after development and before dispersal. Before the study began, students searched the area to find a representative sample of the population. Plants were marked with a numbered metal tag below the litter surface (so that ginseng poachers could not see the tags) and mapped with a laser range finder. The laser range finder generates a precise map with distances and directions from one plant to another. These data allowed us to find existing plants more easily with a metal detector. These populations were used in previous studies, and many plants within the populations were already mapped and tagged from these studies. At the beginning of each year, students searched the area for unmarked plants. When we found a new plant, we marked it with a new metal tag, and mapped it with the laser range finder.

2.2. Population Matrix Models and Mathematical Analyses

Matrix population models predict population growth by breaking up populations into mutually exclusive classes, and evaluating the probability of moving from one class to another. This is accomplished by building a transition matrix (**A**) comprised of the probabilities for each possible transition between classes. This transition matrix is multiplied by a vector ($\mathbf{p_t}$) representing the population at time *t*, in order to obtain the population at *t* + 1 (see Equation 1).

$$\mathbf{p_{t+1}} = \mathbf{A} \cdot \mathbf{p_t} \tag{1}$$

In previous studies modeling *P. quinquefolius* population dynamics, populations were divided into size classes based on leaf number[6,16,17,20]. Charron and Gagnon used a log-linear contingency-table analysis[28] to determine that size (i.e. number of leaves) is a better predictor of fate than age. Therefore, I used size classes to characterize the study populations as well. Usually ginseng produces a maximum of 4 leaves, so I split the populations into 5 size classes, including seeds. A general ginseng transition matrix (Figure 1) contains 4 major types of transition: fecundity ($F_{1,j}$), regression ($R_{i,j}$) (a plant reduces in size the next year), stasis ($S_{i,j}$) (a plant stays the same size), and progression ($P_{i,j}$) (a plant grows the next year). $F_{1,j}$ was calculated from the average number of berries produced per plant in size class *j*, then multiplied by the average number of seeds in a berry, 1.9 seeds/berry[29]. $R_{i,j}$, $S_{i,j}$, and $P_{i,j}$ are probabilities representing the likelihood of a plant in size class *j* coming back the next year in size class *i*. Because this study did not include seed survival and seedling recruitment, the $S_{1,1}$ and $P_{2,1}$ values were taken from an earlier study of ginseng demography in West Virginia[6].

$$\begin{pmatrix} S_{1,1} & 0 & F_{1,3} & F_{1,4} & F_{1,5} \\ P_{2,1} & S_{2,2} & 0 & 0 & 0 \\ 0 & P_{3,2} & S_{3,3} & R_{3,4} & R_{3,5} \\ 0 & 0 & P_{4,3} & S_{4,4} & R_{4,5} \\ 0 & 0 & P_{5,3} & P_{5,4} & S_{5,5} \end{pmatrix}$$

Figure 1. A typical ginseng population transition matrix[6].

The asymptotic growth rate (λ) of a population is the dominant eigenvalue of the transition matrix for that population. Any eigenvalue (λ) and its corresponding eigenvector (**w**) are solutions to equation (2).

$$\mathbf{A} \cdot \mathbf{w} = \lambda \cdot \mathbf{w} \tag{2}$$

It is likely that there is more than one pair of eigenvalues and eigenvectors for a matrix, and the dominant eigenvalue is the one with the largest magnitude. The corresponding eigenvector represents the stable size distribution. A matrix was constructed for each population using the transition probabilities and fecundity values, and asymptotic growth rates (λ) were calculated. The bootstrap resampling method was used to calculate 95% confidence intervals of λ for each population. The relationships between harvest rate and growth rate were modeled, as was the relationship between harvest rate and time to extinction. Lastly, the elasticities of λ for the 4 demographic transition types were calculated, and the stable size distribution for all the populations was determined. All mathematical analyses were performed in MATLAB (MATLAB and Simulink Student Version, MathWorks; Natick, MA).

3. Results

Only the SC and MP study populations had significantly positive growth rates, when poaching was removed from the model (Figure 2). Only the MC population had a significantly negative growth rate. The reference line at λ=1 in Figure 2 separates growing populations from declining ones. A population with a growth rate larger than 1 is growing, and any population with a growth rate less than 1 is declining. The results for the PC and LB populations were inconclusive, as they contained λ=1 in their confidence intervals and therefore the range of error comprised values both greater than and less than 1. The direct effects of poaching, i.e. removal of plants from the population, did not affect the fate (survival or extinction) of any population, however indirect effects like trampling are more subtle and were not quantified. The SC population was most resistant to simulated harvest, as it could withstand harvest levels up to 39% with no significant risk of extinction (i.e., with a significant positive growth rate), and up to 93% with nonthreatening extinction risk (its confidence interval contains 1). None of the other populations could be harvested without a significant risk of extinction (Table 1). Lastly, because the MC population was significantly declining, it was threatened even in the absence of harvest.

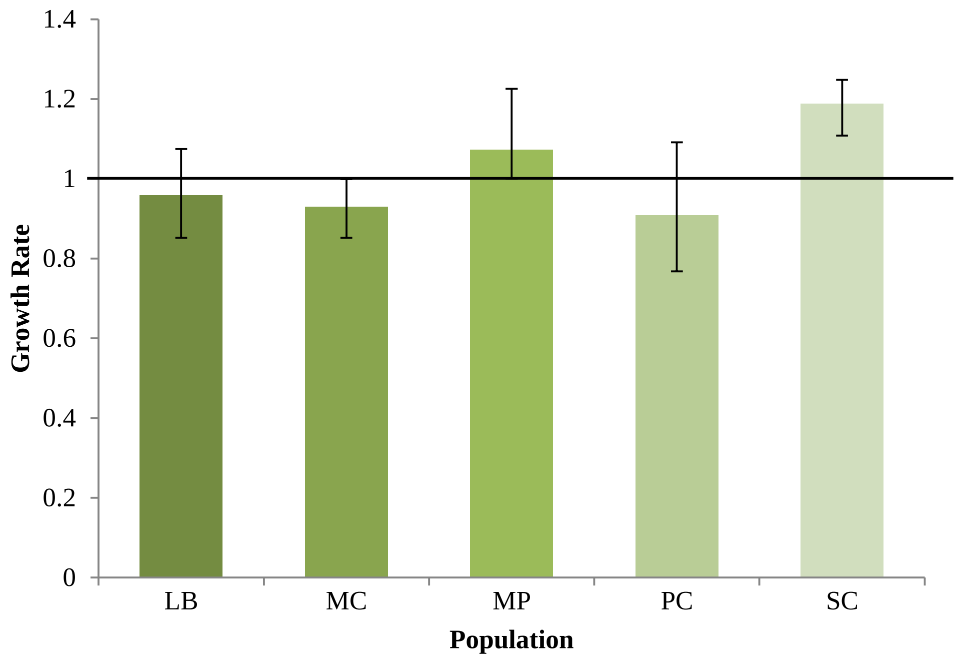

Figure 2. Asymptotic growth rate with 95% bootstrap confidence intervals for the 5 study populations.

Table 1. The maximum harvest allowed at two risk levels. Significant risk means the lower 95% confidence level is below 1. Threatening means the upper 95% confidence level is below 1.

Risk Level	LB	MC	MP	PC	SC
Significant Risk	0	0	0	0	39.3
Threatening	81.2	0	74.8	57.7	92.7

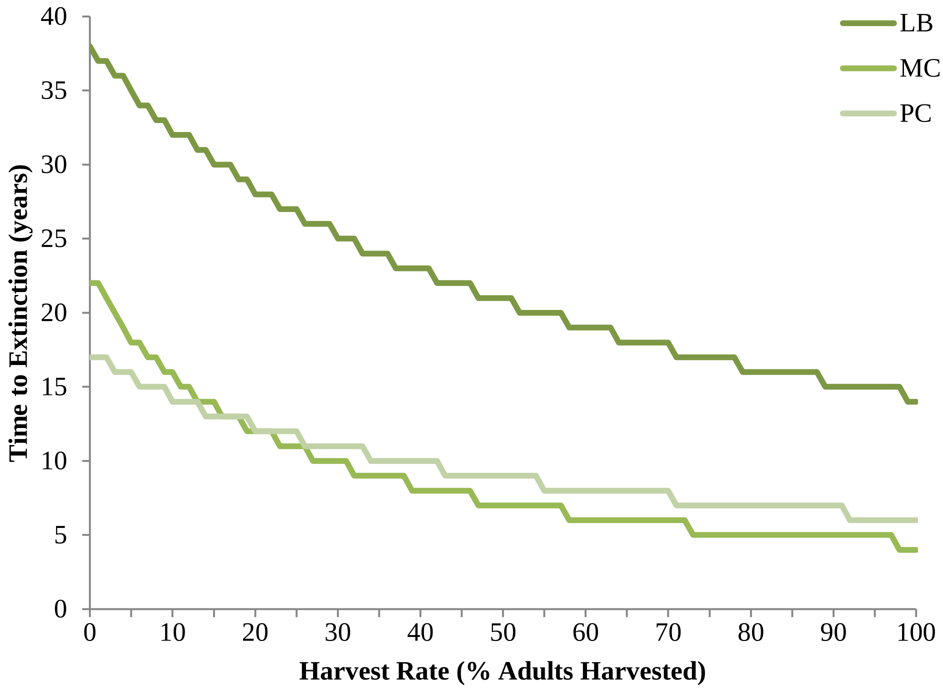

Figure 3. Decreasing times to extinction threshold (20% of original population size) with increasing harvest pressure for the PC, LB, and MC populations.

Of the declining populations, the LB population was declining more slowly, while the PC and MC populations were declining at a faster rate (Figure 3), and even under very light harvest pressure PC and MC would cross the extinction threshold within 15 years.

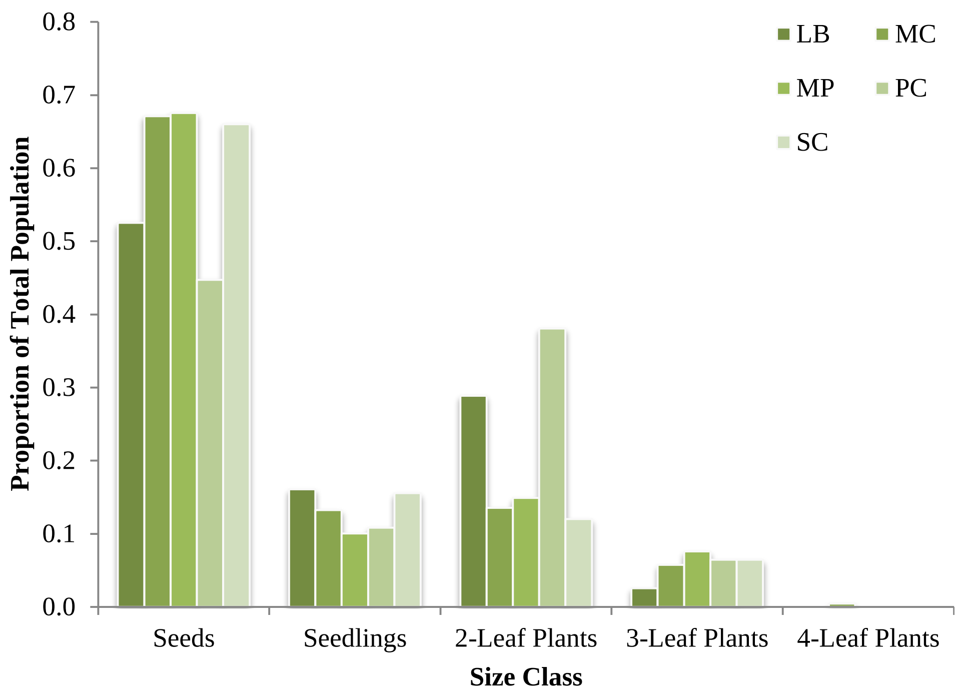

Figure 4. Stable size distribution of the populations.

The MC, MP, and SC populations had similar stable size distributions. Both the LB and PC populations had relatively smaller proportions of seeds at their stable distributions, and relatively larger proportions of 2-leaf plants (Figure 4). Only the MC population had 4-leaf plants in its stable distribution.

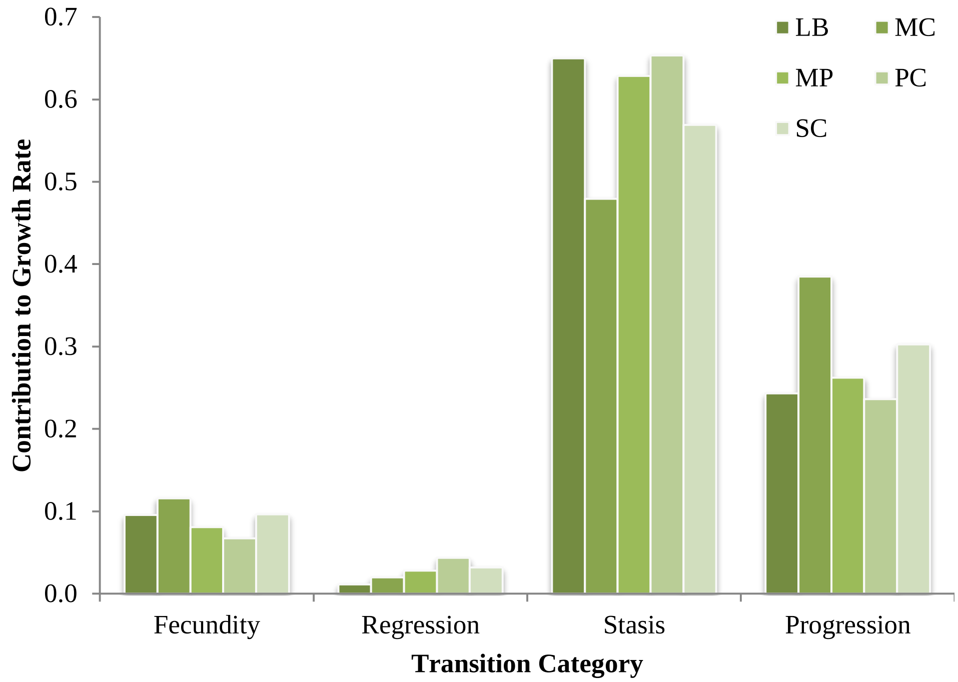

Figure 5. Elasticities of lambda to the four major transition types: fecundity, regression, stasis, and progression. Fecundity is the number of viable seeds produced. Regression, stasis, and progression respectively refer to a plant growing a smaller, similar, or larger number of leaves in the next year.

All populations except the MC population had similar elasticity values for the four demographic transitions. In the MC population, progression had a relatively larger affect on λ and stasis had a relatively smaller effect on λ (Figure 5).

4. Discussion

The populations with the highest risk of extinction are the PC and MC populations, because they have a potential for extinction within 5-15 years, depending on harvest level. The LB and MP populations are not in immediate danger of extinction, however with any harvest comes a significant risk of extinction for either of these populations. The LB population is not projected to reach the extinction threshold for 20 to 30 years, provided harvest of adults remains below 50%. The MP population has a positive growth rate in the absence of harvest, but even relatively low harvest could bring the growth rate below 1. The MC population was in a statistically significant decline, and proactive measures should be adopted if this population is to survive. The SC population does not appear to be under any immediate threat, with a growth rate well above 1. It is difficult to estimate actual harvest levels on any particular population, because harvesting is usually done in private, and harvesters are generally secretive about their harvesting locations. However, in an attempt to estimate possible harvest levels in known ginseng populations, Mooney and McGraw used 4 trained individuals who could identify ginseng, but were not familiar with the site to simulate harvest[8]. Given 2 hours to search, each one harvested on average 26% of the legally harvestable plants, and cumulatively they harvested 60% of harvestable plants in the population.

There was large variability in the estimates of λ, however these results showed that harvest regulations cannot be applied uniformly across populations in western North Carolina. Even among the three geographically close populations (PC, SC, LB), one population (SC) had a significantly higher growth rate. Neither the elasticity values nor the stable size distribution showed a difference between the growing and declining populations in terms of those demographic traits. The elasticity analysis showed that conservation measures should concentrate on the survival of plants already present in the population, as they have the greatest contribution to λ in all 5 populations.

There are many different sources of possible error in modeling. As always, bias in data collection is a concern. When searching for new plants, we were biased towards finding larger plants while missing smaller, less conspicuous plants. This size-based bias is only an issue among size classes when analyzing the current population size distribution, or when the sample size of a size class is too small to give an accurate estimation of transition values. Fortunately, smaller plants were much more common in the populations, so sample size of the smaller size classes was probably not an issue. Much more relevant is the use of seed survival and seedling recruitment data that were borrowed from a previous study on ginseng in West Virginia. These values have a large effect on the dynamics of the population, because seeds are the most numerous size class, and because stasis and progression were the two most influential transitions. Future studies should include seed survival and seedling recruitment from local populations to eliminate this possible source of error. There is also error that comes from the parameterization of the model itself. When choosing size classes, there has to be a balance between choosing too many classes, and too few. Using more size classes will necessarily reduce the number of replicates in each individual class, eventually resulting in less accurate transition values. On the other hand, increasing the number of individuals in each size class by using fewer classes results in inaccurate transition values because all of the individuals in a size class are treated as identical when they are not. Also, the effect of herbivory by white-tailed deer has been ignored. From personal observation, herbivory seems to be more prevalent in the MP and MC populations. Farrington et al. showed that deer herbivory does not negatively impact population growth rate in the presence of harvest, because eating a plant's leaves and/or berries effectively hides that plant from harvesters[20]. However, herbivory does negatively impact population growth in the absence of harvest by consuming and destroying seeds of reproductive plants[22], and therefore adding the effect of harvest with the effect of herbivory will incur some error.

These results are from a preliminary study, with only a single year's worth of transition data. The study will have to continue for several more years before more meaningful conclusions can be drawn from the data. Most published studies use at least 3 years of data[6,14-19], and even this is too short term to present a good overall description of the demographics of a population of long-lived perennial herbs[11-13]. Matrix population models for ginseng require several years of data to accurately estimate the frequency of rarer transitions[20]. In addition to better accuracy and precision, a larger data set will allow for more advanced analyses. Genetic studies have found that ginseng exhibits clumping, where individuals in close proximity are genetically similar[30]. This indicates that seeds usually do not disperse far from the parent plant. A complete model should include possible demographic differences among clumps due to environmental variability and differences in density. Unfortunately, this option will only be available with longer-term data. It is also important to consider environmental and demographic stochasticity[12], but again this requires more data than is available at the moment. My primary goal is to develop long term demographic data that is suitable for matrix population modeling. In seven to ten years, the dataset will be robust enough to model a previously unexamined portion of American ginseng's range.

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