University of North Carolina Asheville
Journal of Undergraduate Research
Asheville, North Carolina
May 2023

Population Demographic Modeling of American Ginseng (*Panax quinquefolius* L.) Populations in Western North Carolina

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Abstract

American ginseng (*Panax quinquefolius* L.) is an herbaceous perennial understory plant distributed throughout deciduous forests in eastern North America. Ginseng is widely sought-after for the medicinal compounds (ginsenosides) in its roots. A majority of harvested ginseng is sold for use in traditional Asian medicine. Overharvest and scarcity of Asian ginseng (*Panax ginseng* L.) led to mass exports of American ginseng to Asia starting in the early 1700s. American ginseng has since been overexploited and has experienced major population declines. Wild ginseng harvest is regulated in many states to conserve and protect populations of the species, yet illegal poaching still occurs. Ginseng is slow growing and typically reemerges each year from its roots as leafy stems in different size classes, which are often categorized by the number of leaves present. Their above-ground vegetative growth year-to-year can increase, stay the same size class, or revert back to smaller size classes (typically in response to stress). Using several years of demographic data collected between 2011 and 2022 from six western North Carolina populations, demographic models were created to understand patterns, demographic change, and the long-term viability of these populations. The demographic monitoring of these populations did not include extensive fertility data (seed production and seed fate). Instead, published fertility data from a study in West Virginia were used. Models can be used to gain a better understanding of the population dynamics of wild ginseng in western North Carolina as well as simulate the effects of different harvesting intensities, which can aid in developing sustainable harvesting protocols. The developed models predicted all six populations to have a positive growth rate ($\lambda>1$). Modeled predictions did not match observed demographics. This suggests that the developed model does not accurately capture demographic data. This work also highlights demographic monitoring work, such as collecting regionally specific fertility data, that is needed to more accurately model wild ginseng populations in western North Carolina.

1. Introduction

American ginseng (*Panax quinquefolius* L.) is a wild herbaceous perennial understory plant distributed throughout North America. Ginseng is widely sought after for medicinal compounds, ginsenosides, with its roots commonly used in traditional Asian medicine[1]. In traditional Chinese medicine, “yin-yang” is a theory in which the balance of “yin” and “yang” is related to internal harmony. American ginseng is said to have cooling effects (yin), while Chinese ginseng (*Panax ginseng* L.) is said to have warming effects (yang)[2]. Overharvest and scarcity of Chinese ginseng led to mass exports of American ginseng to Asia starting in the early 1700s. American ginseng has since been overexploited and has experienced major population declines across its range[3]. Wild ginseng harvest is regulated in many states to conserve the species, yet illegal collection and overharvesting still occur[3]. Appalachian ginseng populations are at risk due to habitat destruction and climate change but most notably, root collection[1].

Ginseng plants are perennial. Each year a determinate stem with compound leaves emerges from the root in the spring and then dies back in the fall (Figure 1). Ginseng is slow-growing, reaching reproductive maturity in 3-8 years, and long-lived, with accounts of plants of at least 60 years old[1,3,4]. Ginseng goes through distinct growth stages (seed, one-leaf, two-leaf, three-leaf, and four-leaf) and can sometimes revert back to earlier stages, generally in response to stress[1] (Figure 2).

Population demographic modeling of ginseng determines transition probabilities of distinct size classes over time (Table 1). Population demographics, including measures of the number of plants, leaflets, and fecundity of American ginseng were first modeled for a population in Missouri[5]. In 1991, in Quebec, Canada, four populations were monitored with more in-depth population dynamics which included separate age classes[3]. Population dynamics data can be used to model the effects of different harvesting levels[1,6,7]. The effects of different harvest intensities and behaviors of various degrees of compliance with local regulations on West Virginia ginseng population has been modeled and observed[7]. Information from population demographic and harvest simulation studies can be used to guide local harvesting regulations aimed at sustaining the viability of populations.

Studies on southern Appalachian populations of ginseng are heretofore limited. Since 2008, faculty from the University of North Carolina Asheville and Warren Wilson College have led student researchers in monitoring the demographics of local American ginseng populations plants. This study uses those data to generate population demographic models that can be used to forecast the long-term viability of wild populations of different sizes in western North Carolina. A goal of this study is for components of it to be used to guide local regulations on sustainable root harvest.

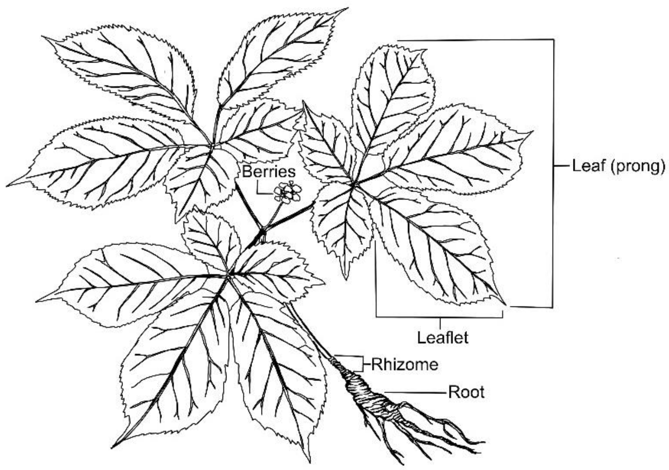

Figure 1. Anatomy of a 3-leaf ginseng plant. Image made by author.

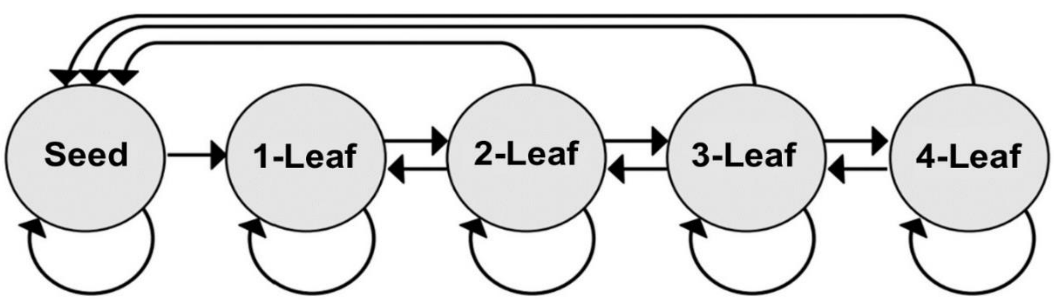

Figure 2. Life cycle diagram for *Panax quinquefolius* showing possible yearly transitions (modified from Mooney & McGraw[8]).

Table 1. Transition probability matrix format for ginseng life stages.

	Seed	1-Leaf	2-Leaf	3-Leaf	4-Leaf
Seed	Probability that a seed remains a seed	Average number of seeds produced by 1-leafs	Average number of seeds produced by 2-leafs	Average number of seeds produced by 3-leafs	Average number of seeds produced by 4-leafs
1-Leaf	Probability that a seed transitions to a 1-leaf	Probability that a 1-leaf remains a 1-leaf	Probability that a 2-leaf reverts back to a 1-Leaf	Probability that a 3-leaf reverts back to a 1-leaf	Probability that a 4-leaf reverts back to a 1-leaf
2-Leaf	Probability that a seed transitions to a 2-leaf	Probability that a 1-leaf transitions to a 2-leaf	Probability that a 2-leaf remains a 2-leaf	Probability that a 3-leaf reverts back to a 2-leaf	Probability that a 4-leaf reverts back to a 2-leaf
3-Leaf	Probability that a seed transitions to a 3-leaf	Probability that a 1-leaf transitions to a 3-leaf	Probability that a 2-leaf transitions to a 3-leaf	Probability that a 3-leaf remains a 3-leaf	Probability that a 4-leaf reverts back to a 3-leaf
4-Leaf	Probability that a seed transitions to a 4-leaf	Probability that a 1-leaf transitions to a 4-leaf	Probability that a 2-leaf transitions to a 4-leaf	Probability that a 3-leaf transitions to a 4-leaf	Probability that a 4-leaf remains a 4-leaf

2. Methodology

Population demographic measures were taken from different ginseng populations (CF, PC, HG, MP, KF, and SC) located in Buncombe and Jackson Counties in Western North Carolina between 2011 and 2022. For each population, detailed surveying, tagging, and mapping of all plants within an area were conducted. Each subsequent year, populations were resurveyed once between May and early August. Surveying years for each population were: PC (2011-2021), SC (2011-2018), MP (2013-2021), KF (2014-2022), CF (2014-2022), and HG (2014-2022).

To analyze these data, plants were separated into 5 size classes; seeds, 1-leaf, 2-leaf, 3-leaf, and 4-leaf. Plants with 5 or 6 leaves are rare and were added to the 4-leaf size class. Though limited data on berry production were taken in some populations, depending on the timing of the annual survey, inconsistencies among sites led us to exclude these data from models. To get accurate fecundity estimates, repeated surveys are needed during fruit production and maturation in later summer and fall[1]. Furthermore, seed germination data were not collected as part of this study's fieldwork. Instead, we used data from populations in West Virginia outlined in Van der Voort and McGraw (2006) for the fecundity and germination measures[7].

Only data from plants found in two consecutive years were analyzed to ensure that the fate of the plant was known because a plant not found in a consecutive year could have been poached, gone dormant, or suffered severe herbivory. Transition probability matrices for each year-to-year transition were constructed by dividing the total of plants that stayed in a specific transition class by the total number of plants in the initial year size class. For example, the number of plants that has 2 leaves in the initial year and had 3 leaves the following year was divided by the total number of plants that had 2 leaves in the initial year. For each population, the average of each transition probability was calculated.

Data were analyzed using the *popbio* package in R (Version 10.0.22621.1555)[9,10]. *Popbio* can be used to model population growth over time. The function "pop.projection" was used by defining projection matrices (transition probability matrices), initial stage vectors (initial year population demographics), and the number of iterations (years) for each population[9]. *Popbio* uses growth rate (λ) as the dominant eigenvalue and calculates these from the transition matrices. To evaluate the accuracy of these models, for each population, a calibration model was created by using demographic data from the first year of detailed observation as a start vector, then running each model for the number of years between the first and last year of census (Figure 3). Modeled population structure in the final year was then compared to the observed final year population structure using Chi-squared tests.

To simulate different harvesting intensities with the model, demographic data from the final year of observation of one population, PC, was used as a start vector but 3 and 4-leaf plant demographics were altered to reflect 5%, 10%, and 20% reductions. The model was then run for 20 years (Figure 4). This was only done with PC as it was the only population in which the calibration model showed a successful prediction of population growth.

3. Results

The model successfully predicted growth in only 1 population, PC, where there was no significant difference between modeled and observed final population structure ($p = 0.244$). The total modeled population size for PC in 2021 was approximately 282 individuals, while the actual observed size was approximately 267 individuals. For the 1-leaf, 2-leaf, and 3-leaf size class totals in 2022, the modeled predictions were greater than the observed values while the seed and 4-leaf size classes had greater observed values than the modeled ones. All other populations did not successfully predict growth as they differed in modeled and observed final structure ($p < 0.05$) (Figure 3). The calculated λ values for each population are: CF (1.18), PC (1.06), HG (1.03), MP (1.15), KF (1.03), SC (1.06). Preliminary projection models simulating different harvest intensities (5%, 10%, and 20%) from the PC population showed an increase in the population's size of all size classes following a 20-year period.

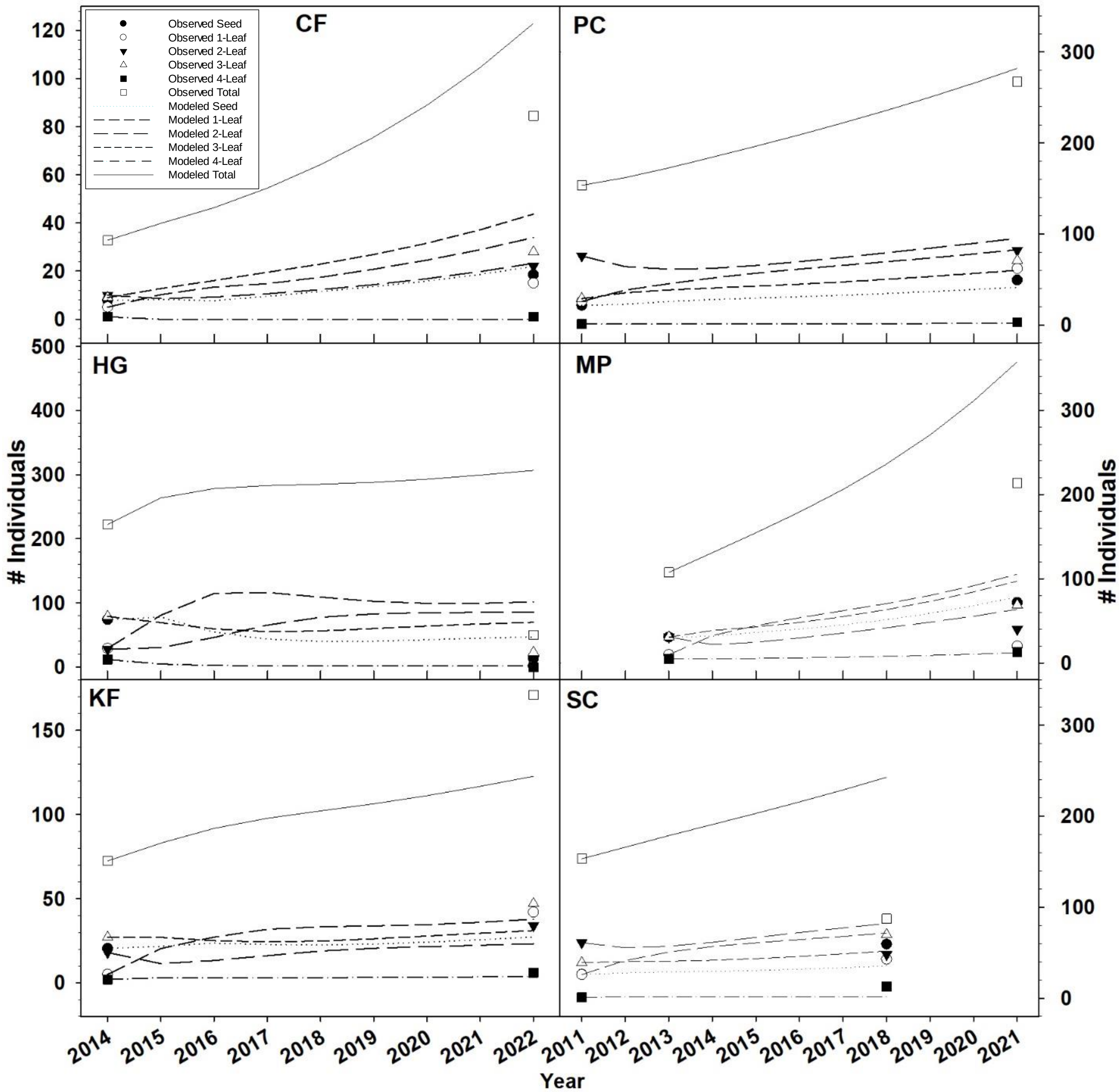

Figure 3. Modeled population demographics for each size class and total population numbers over time (lines) compared to initial and final observed abundances of each size class and total population number. *Note that Y-axes have different scales based on population size.

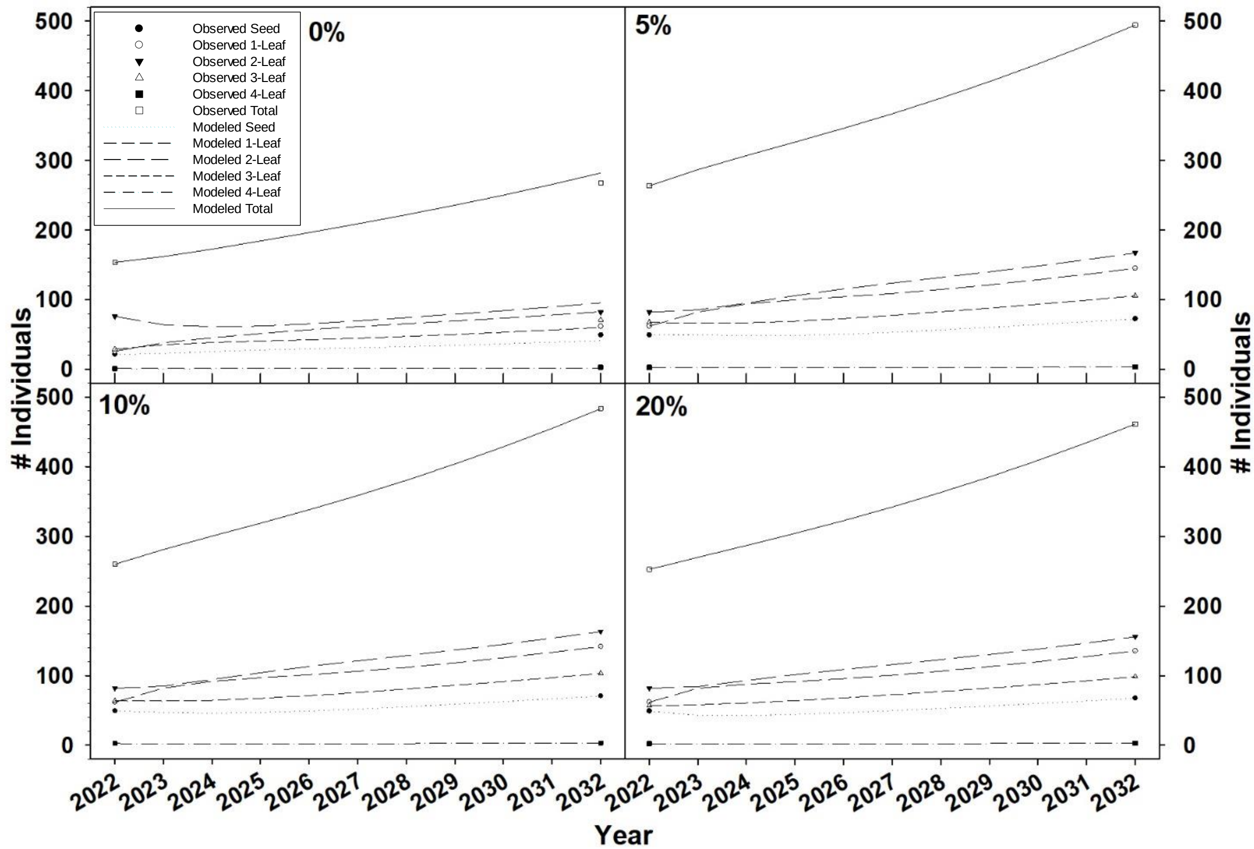

Figure 4. Population growth under simulated harvest intensities (0%, 5%, 10%, and 20%) for 20 years in population PC.

4. Discussion

Compared to observed values, the modeled predictions were significantly different for 5 of the 6 populations, this suggests inaccuracies in the model. Discrepancies between the modeled and observed data are likely due to unrealistic fecundity and germination measures. The data used for these parameters from McGraw et al. were collected from populations in West Virginia[1]. Differences in climate and population genetics can impact regional fecundity and germination estimates. 4-leaf plants from four populations in southern Quebec, Canada produced an average of 26.46 seeds per plant, while 4-leaf plants in a population in Missouri produced an average of 12 seeds per plant[3,5]. These differences imply that there are regional fecundity differences. A study comparing genetic diversity within and among different ginseng locations in North Carolina and northern Virginia found that there are clear genetic differences within geographically separated ginseng locations but no clear differences among locations[11]. Though, extensive research on regional differences in the reproductive genetics of ginseng is not available and could be a factor of regional differences. McGraw et al. 2013 also used different criteria for size class classification than this study. This and other studies use the number of leaves for size class classification while McGraw et al. 2013 used the total leaf area[3,5,1].

The germination data used were also collected in an experiment that monitored seeds in seed cages which prevented herbivory[12]. Research on specific ginseng seed herbivores is limited, but there is evidence of natural populations experiencing seed herbivory from animals including deer and birds, which would impact a population's overall germination rate[1]. Therefore, it is likely that the germination data used are unrealistically high.

The simulated harvest model for the PC population shows that the population is continuing to increase under all harvest intensities. This result is however preliminary due to the suspected inaccuracy in the model. Van der Vort and McGraw examined the effects of different harvest intensities based on local West Virginia regulation compliance[7]. The ambient control group (no harvesting) and steward harvested group both had positive growth rates while the compliant and non-compliant harvested groups had negative growth rates[7]. The non-compliant group featured the removal of 25% of all 2-leaf, 3-leaf, and larger plants while the compliant harvest group removed 25% of the 3-leaf and larger plants[7]. These findings suggest that even under compliance with some local regulations, populations can experience declines. Studies such as this can encourage regulations to include harvest intensities/practices that still result in an increasing population growth rate[7].

Calculated λ values predict that all 6 populations are experiencing positive growth ($\lambda > 1$). These data were calculated using the same West Virginia fecundity and germination data for all populations and likely mask differences in individual population fecundity. Again, overestimates of seed survival and germination could make these values unrealistically high.

Though the parameters of the models presented in this research are inaccurate, this research is important because it highlights the need for future work. Future work should include collecting fecundity and germination data from Western North Carolina ginseng populations. Fecundity data collection would require monitoring a population multiple times throughout the growing season. Germination experiments should use regional seeds and should be designed to monitor the effect of herbivory on germination rates. Other R packages such as *popdemo* should also be considered in future work. Perturbation analyses in this package could give insights into how changes in different size classes affect population stability[13]. If perturbation analyses show that a particular size class has a greater effect on population stability, this could emphasize the need for the protection of that size class. For example, orchids have similar life stage transitions as ginseng and a study of two species of orchids in New Hampshire used life-table response experiments and found that fecundity differences contributed the most to the difference in population growth[14]. This study concluded that conservation efforts should focus on the survival of adult orchids as they produce seeds[14]. Data of our populations show that plants with two or more leaves can produce seeds. In North Carolina, the Nantahala and Pisgah National Forests did not issue ginseng harvest permits in both 2021 and 2022[15]. However, in the years in which permits were issued, harvest was only permitted for plants with three or more leaves[16]. If perturbation analyses on these populations imply that reproductive plants should be the focus of conservation, this may influence further suspension of permit issuing. With these adjustments, these models could be improved and used to better inform the local conservation status of the species and local regulations on harvesting.

5. Acknowledgments

I thank the dozens of students from the University of North Carolina at Asheville and Warren Wilson College who have helped conduct field surveys throughout the years. I would like to thank my faculty advisor, Dr. Jonathan Horton for his expertise and guidance throughout the entirety of this project. I would also like to thank Dr. Jennifer Rhode Ward and Dr. Alisa Hove for their guidance in the field and various other components of this project as well as Dr. Irene Rossell for her input and feedback.

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