Final Report for Travel and Conservation Grants provided by the Foundation for the Conservation of Salamanders in support of Weller's Salamander research

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Faced with climate change, organisms either adapt in place or move—or they go extinct. Relative to dispersal, adaptation in response to environmental change remains poorly understood[1]. Fortunately the recent development of molecular techniques for detecting adaptation in wild populations is making it easier to evaluate this response[2]. These developments offer important benefits for conservation practice in a dynamic world, since adaptation can improve the ability of species to persist under the synergistic effects of climate change and habitat fragmentation.

My research investigates the interaction of local adaptation and gene flow in terrestrial salamanders of the family Plethodontidae (which lack lungs and breathe through their skin), a group being disproportionately affected by climate change[3]. These animals have limited dispersal capabilities and are highly sensitive to changes in climate[4]. In eastern North American forests, salamanders are the dominant and most abundant vertebrate predators, where they play a fundamental role in ecosystem structure, function, and stability[5]. These characteristics—environmental sensitivity and ecological importance—make salamanders an excellent indicator taxon for climate change research.

With the support of the Foundation for the Conservation of Salamanders, I have been able to work with Weller's Salamander (*Plethodon welleri),* a high-elevation Southern Appalachian endemic species of conservation concern (right). Its small range (Fig. 1) is located in a global center for forest and freshwater systems biodiversity, including a global hotspot for salamander biodiversity[3]. Appalachian salamanders are under threat from a diversity of causes, most of which are not well understood[6–9]. My research is providing basic ecological data on this understudied species of conservation concern, and is illustrating a novel approach to understanding local adaptation, adaptive potential, and the effects of habitat fragmentation. These results are important both to salamanders in general and to other taxa of concern as we work to implement effective conservation practice in a dynamic global environment[10].

Research questions: My research is based in the expanding field of landscape genetics, which addresses the interaction of landscape features and evolutionary processes based on neutral and adaptive genetic diversity[2,11]. I use a "genomic" approach, in which high-throughput genetic sequencing is used to develop a very large number of molecular markers. Genomic methods are increasingly being used to quantify adaptive potential in wild species with the goal of improving conservation decision-making[12–14]. Within this framework, I am addressing the following questions:

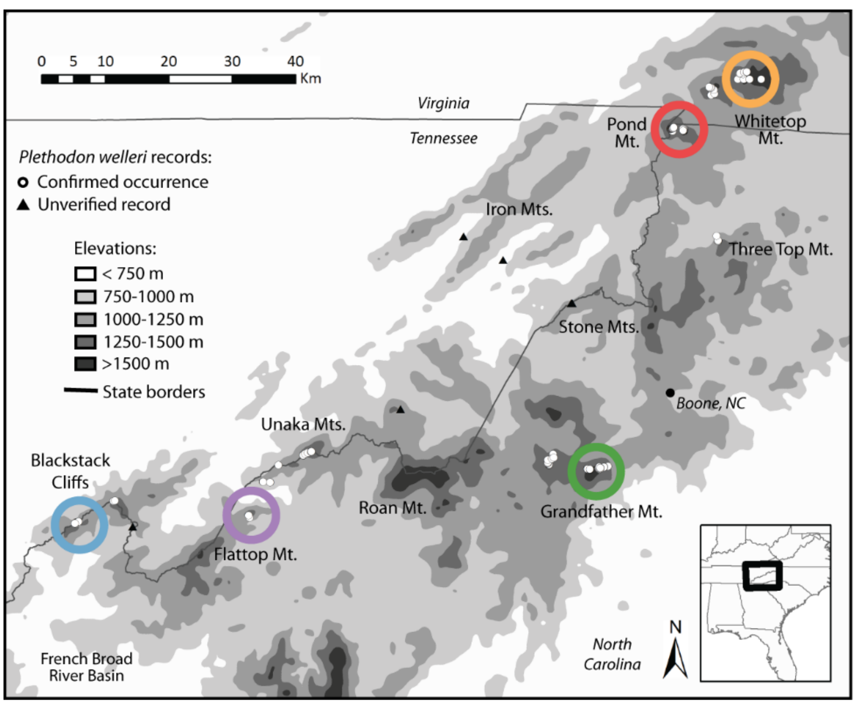
- Over what spatial scales are populations separated by geographic distance also genetically different?
- To what extent are populations locally adapted to different microclimates?
- To what extent does dispersal facilitate or isolation impede the ability of populations to track or adapt to local microclimatic variability?

I am addressing these questions by investigating relationships among neutral and adaptive molecular markers, microclimate variables, and geographic separation distances.

Results to date & continuing research: Funding from the Foundation for the Conservation of Salamanders has allowed me to:

- Travel to eight study sites to collect data on Weller's salamander populations, including measurements, microhabitat data, and (non-lethal) genetic samples;
- Travel to five study sites to collect high-resolution temperature and relative humidity data that are used to model environmental covariates relevant to salamander habitat use and physiology;
- Genotype more than 100 individual genetic samples at thousands of single nucleotide polymorphism (SNP) markers using double-digest RAD-sequencing[15].

Preliminary analysis of sequenced genetic samples has resulted in the identification of 642,000 "RAD tags" (short reads) across 128 individuals, with 31,584 SNP markers in common in at least 80% of these individuals. Analysis of Weller's salamander genomic, environmental, and spatial data indicates significant differentiation at neutral markers both across mountain peaks (Fig. 1, right) and within elevation gradients indicating restricted gene flow. Additionally,



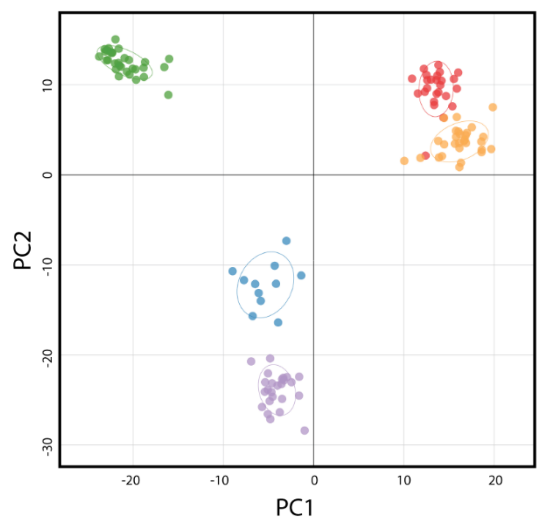


Fig. 1. Weller's salamander range (left). Circled populations have been genotyped and colors correspond to individuals plotted in principle component space (right), illustrating genetic differentiation across populations.

preliminary analysis of markers potentially under selection[16] indicates that Weller's salamander populations are locally adapted to temperature across their range. We are currently analyzing genetic data from an additional four populations. Results from these analyses will be incorporated into an adaptive management plan for Weller's salamander (see below).

Conservation importance: While a number of studies have found evidence for adaptive responses to climate in amphibians, indicating that adaptation has the potential to mitigate climate change in these species[17], it remains unknown if wild populations of amphibians will be able to adapt to climate change at the rate and magnitude that it is occurring. My research is directly assessing the adaptive potential of Weller's salamander populations in an effort to inform this very large gap in our understanding of species responses to climate change. Besides imposing direct selective pressures (e.g. warming and drying conditions), climate change also contributes to habitat loss for montane species. Models of climate change impacts on Weller's salamander populations at Whitetop Mountain (VA) have indicated complete habitat loss by 2070[18]. Additionally, habitat loss due to deforestation, increasing fragmentation, and forest alteration (e.g. acidification due to acid rain and fog and tree loss due to invasive pests) are also major concerns for Weller's salamander. For example, it is known that logging can have dramatic impacts on salamander populations, including very long recovery times and even complete extirpation[19]. This is especially problematic for a species with such a limited distribution. Many of the known Weller's salamander populations are on protected land, but most of these areas are still subject to logging and also see intense recreational use. Additionally, many public and private lands are still in need of surveying, with most of these private lands under increasing pressure from development and expanding human populations.

I will be incorporating results from my research into an adaptive management plan[14,20] for Weller's salamander. This includes addressing the following questions that are critical to effective conservation planning for this species: What is the adaptive potential of Weller's salamander populations? Do populations have sufficient genetic diversity for an evolutionary response to climate change? Will these populations be able to tolerate climate change in place? How is genetic diversity distributed across populations? Are some populations more vulnerable to extinction than other? What are effective population sizes of these populations? Are the populations completely isolated, and if so, would some populations benefit from assisted gene flow? How much of

Weller's salamander habitat is on public vs. private land? What recommendations can we make for conservation prioritization based on genomic data? By addressing these and other questions, my research will be making both a strong scientific and policy contribution to the effective conservation of Weller's salamander. Finally, and more broadly, my work is helping us better understand the capacity of species to adapt to changing conditions, and what actions will be most effective to conserve biodiversity under global change.

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