**Assessing the Effects of Forest Management and Wildfire on Populations of New Mexico's Endemic Salamanders**

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## Introduction

Two endemic salamanders occur in the mountains of New Mexico: the Jemez Mountains salamander (*Plethodon neomexicanus*) and the Sacramento Mountain salamander (*Aneides hardii*). *P. neomexicanus* is federally-listed as Endangered and *A. hardii* is state-listed as Threatened. Relicts of past glacial events, populations of these species remain perched on cooler, moister mountaintops in mixed conifer forests, one in the north-central and the other in the south-central part of New Mexico, surrounded by lower elevation landscapes of pinyon-juniper and other arid-land plant communities. Both species are at risk of decline or extirpation because of their relatively small geographic distributions and impacts to their populations from historic timber harvesting and more recent changes in forest structure; increased occurrence of moderate- and high-severity fires within their ranges; and warmer, drier weather patterns associated with climate change. Narrow thermal tolerances limit both species' abilities to cope with alterations in microclimate associated with changes in forest structure, and their elevational position on the upper slopes of mountains restricts their ability to shift their distributions upward in response to a warming climate. Furthermore, atypical wildfire activity can influence species' short-term and long-term survival and habitat availability. Comprehensive studies of the population demography, magnitude of historic disturbances, and microclimatic factors that influence salamander surface activity in addition to more accurate estimates of detection probabilities are needed to understand apparent differences in the population trajectories between the two species and inform guidelines for species surveys and forest management activities. Although both species are discussed in this report, the focus for this project is on *A. hardii*.

Despite the existence of historic unpublished accounts documenting population declines over the past two decades for both species (with *P. neomexicanus* apparently exhibiting more severe declines, formal and comprehensive assessments of population size and structure have not been undertaken for either species in recent years. In the 1960s through the 1990s, hundreds of *P. neomexicanus* could be captured in a year. Although extensive logging likely impacted populations, stand-replacing fires between the late 1990s and 2013 have apparently eliminated entire populations and significantly reduced the size of other populations. To our knowledge, prior to our initiation of mark-recapture efforts in 2018, the last study to use mark-recapture methods to estimate population size for this species was completed in 2000 (Cummer and Painter 2007). A recovery plan for this federally endangered species has not yet been developed.

It has been suggested that populations of *A. hardii* may be more resilient than *P. neomexicanus* populations to landscape-altering disturbances such as broad-scale logging and wildfires. To our knowledge, the last attempt to study populations of *A. hardii* using mark-recapture techniques, which was unsuccessful, occurred nearly two decades ago (Haan and Desmond 2005). Apparent contrasts in population sizes and trajectories between these two endemic plethodontid salamanders present an opportunity to identify the factors responsible for the differences, which ultimately may be useful for developing a recovery plan for *P. neomexicanus* that includes habitat restoration guidelines and identifying populations of *A. hardii* that would benefit from habitat restoration.

The unique life histories of these completely terrestrial salamander species have presented challenges to reliably detecting them during surveys, leading biologists to call for assessments of detection probability for both *P. neomexicanus* and *A. hardii* (Cummer and Painter 2007). Both species spend most of the year below ground and return to the surface during the warm, wet monsoon season, generally from July to September. However, they likely move above and below ground during the monsoon season in response to changes in microclimate suitability at the surface, thereby limiting the times and conditions under which they can be found during above-ground surveys. To our knowledge, aside from our research begun in 2019, no previous studies have attempted to quantify detection probabilities for *P. neomexicanus*. One previous attempt (Haan et al. 2007) to assess detection probabilities for *A. hardii* was unsuccessful because plots were surveyed only one time each, yielding a high number of false absences and low predictive power. Surveys designed to quantify detection probability must include multiple visits to multiple plots known to be occupied by salamanders with the goal of capturing: (1) within-season variation in detection probability related to within-season above- and below-ground movements influenced by changes in microclimate, (2) among-season variation in detection probability associated with annual variation in broader weather patterns, and (3) site-level variation in detection probability associated with variation among sites in salamander abundances, habitat and microhabitat structure, and microhabitat availability. Lower apparent abundances of salamanders within populations necessitate increased numbers of plots (when possible) and numbers of plot surveys and, in some cases, surveys over multiple years. Generating detection probability estimates for *P. neomexicanus* and *A. hardii* will be useful for developing species-specific guidelines for surveys to be implemented prior to ground disturbing activities. This will be particularly important for activities that fall within the range and suitable habitats of *P. neomexicanus*, for which survey requirements are currently negotiated with the U.S. Fish and Wildlife Service on a project-by-project basis.

Forest management tools such as thinning and prescribed burning are employed to reduce the presence of fuels that can lead to stand-replacing fires. Limited access to higher elevations in winter and protections for migratory or threatened species, including salamanders, constrain flexibility in implementing forest management activities from December through September within the ranges of both species. Ironically, fire exclusion and restrictions on timing of thinning and prescribed burning activities have led to an increase in the occurrence of high severity fires in higher-elevation forests of the southwest, where ecological impacts of such fires are more severe than in the past (O'Connor et al. 2014), thus increasing the vulnerability of salamander populations and their habitats. Optimal temperatures for surface activity are 11.4°C for *A. hardii* and 12.5°C for *P. neomexicanus* (Williams 1976), but to date, the temperature and moisture levels and durations of those conditions that bring salamanders to the surface or drive them below ground within the monsoon season have not been quantified. Developing an understanding of these temperature and moisture thresholds may allow land managers to make empirically-based decisions to initiate forest management activities such as hand thinning during periods in which microclimatic conditions indicate that salamanders should be below ground and unlikely to be impacted. Such information could allow for greater flexibility in implementing forest management tools within the ranges of both species while still ensuring minimal species impacts from such activities, and could also contribute needed information to a recovery plan for *P. neomexicanus.*

The primary objectives of this project are to: (1) Quantify the population demography of *A. hardii* (population size, density, sex ratio, and age class structure) as related to forest structure, composition, and disturbance history; (2) Evaluate the impacts of wildfire along a burn severity gradient on *A. hardii* occupancy; (3) Calculate detection probabilities for populations of *A. hardii*; (4) Identify the temperature and precipitation thresholds, and durations of those thresholds, that initiate or cause the cessation of surface activity in *A. hardii*; and (5) Summarize results in a way that informs land managers about the status of *A. hardii* in relation to conservation and habitat restoration needs.

## Methods

Standard biosecurity and disease protocols were followed for all surveys. Boots and equipment that contacted soil or salamanders at a site were decontaminated with Virkon Aquatic after each visit to a site, and a new bag was used to handle each salamander.

*Population Demography*

To evaluate the demography of *A. hardii* populations, we established plots for mark-recapture surveys in the White and Sacramento Mountains. In each mountain range, we selected two sites and at each site delineated three 25 x 25 m plots located at least 100 m from one another. In the White Mountains (Smoky Bear District, Lincoln National Forest), plots were established at Big Bear Canyon and Ski Apache; in the Sacramento Mountains (Sacramento District, Lincoln National Forest), plots were established at Lightning Lake and Russia Canyon (Figure 1). Sites were located at least 5 km from one another. We were unable to establish plots in the Capitan Mountains because of their remoteness, challenging driving terrain, lengthy time required to reach suitable habitat, and concerns about our ability to resurvey these sites regularly within the optimal survey timeframe for *A. hardii*.

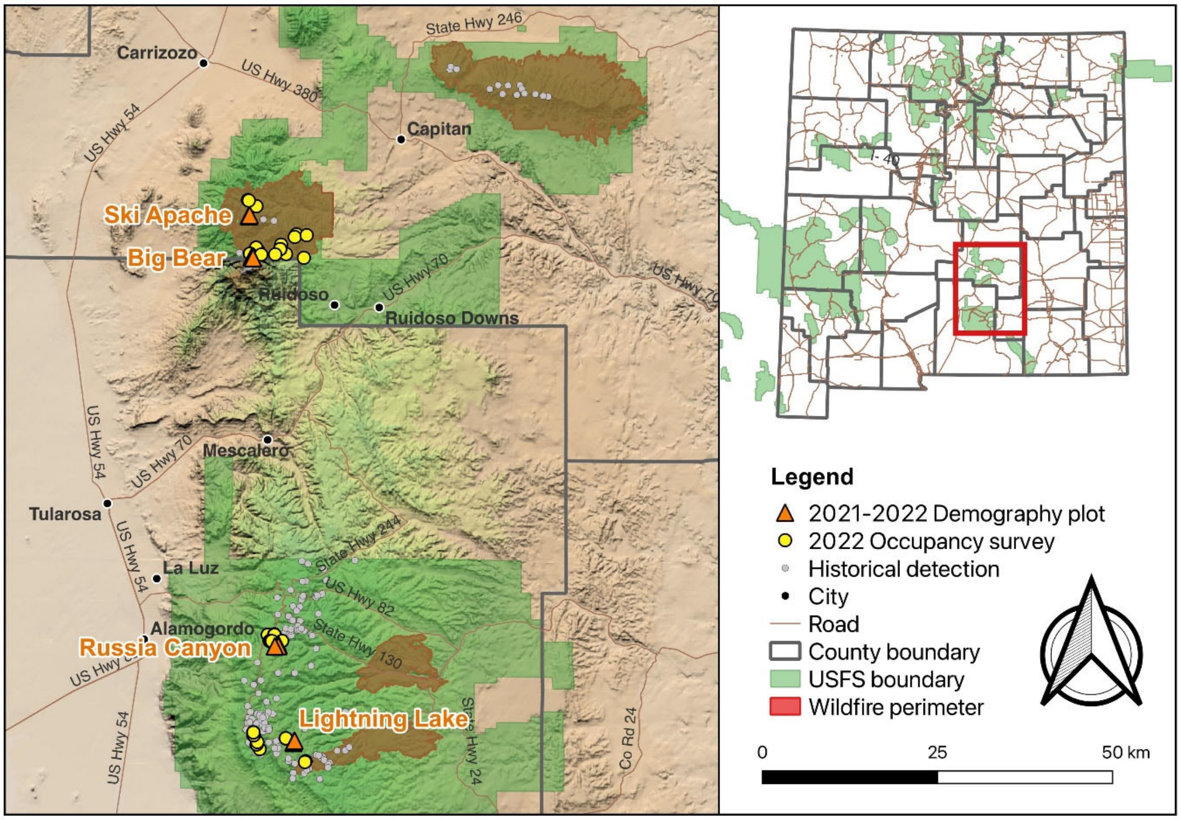


Figure 1. Locations of demography plots and occupancy surveys for the Sacramento Mountain salamander (*A. hardii*) on the Lincoln National Forest in 2022.

We surveyed plots for salamanders every two weeks during the monsoon season (July through August 2022) by turning over all rock and wood cover objects and searching other suitable microhabitats, including bark, leaf litter, and moss mats. We weighed, measured, and determined the sex of all captured salamanders; most captured salamanders were swabbed for pathogens. Salamanders with a trunk length >30 mm (adults) were anesthetized using tricaine methanesulfonate (MS-222). Adult salamanders were then injected (subcutaneously on the right lateral side of the body) with a 9 mm passive integrated transponder (PIT) tag containing a unique numeric code. After PIT tag implantation, salamanders were allowed to recover in fresh water. Smaller salamanders were injected subcutaneously on the venter with visual implant elastomer, a fluorescent polymer applied in unique locations and color combinations to identify individuals. After processing, salamanders were released beneath the cover object where they were originally detected.

We collected microhabitat data for most salamanders captured during population demography surveys. We recorded geographic coordinates and characteristics of the rock or woody cover object under which a salamander was found (rock: geologic type, dimensions, percent embedded in soil, and whether it was layered with other rocks; log: species, dimensions, decay class, percent char on log surface, and whether the log had fallen or been cut). We also recorded percent ground cover by rock, wood, or vegetation (herbaceous and woody) and canopy cover in a 1 x 1 m plot centered on the point of capture.

*Impacts of Wildfire on Occupancy*

To evaluate the impacts of wildfire severity on salamander occupancy, we conducted one person-hour, time-constrained surveys for *A. hardii* in areas that were unburned, burned at low/moderate severity, or burned at high severity within the White and Sacramento Mountains of the Lincoln National Forest. We did not conduct surveys in the Capitan Mountains in 2022 because of the extremely wet conditions in the forest and associated hazardous condition of the primary road used to access the potential survey areas in these mountains. To select survey sites, we used spatial data available on the Monitoring Trends in Burn Severity website (https://burnseverity.cr.usgs.gov/products/mtbs). Each site was surveyed once and measurement and release of salamanders followed the methods described above. No salamanders were marked during occupancy surveys. For most salamanders captured during occupancy surveys, we collected microhabitat data following the methods described above for the population demography plots.

*Detection Probability*

We will determine the probability of detecting salamanders given a particular number of surveys using data collected from the population demography plots in 2022 and 2023. Plots were surveyed every two weeks from July to September 2022, resulting in five surveys per plot. This will be repeated in the 2023 field season. Following completion of field data collection in 2023, we will model detection probabilities for *A. hardii* using a multi-season, time-to-detection modeling approach and determine if detection probabilities differ among sites for *A. hardii*. This information will be used to determine the probability of detecting *A. hardii* given the number of surveys conducted and will provide an empirical basis for determining how many surveys are needed to determine with 95% confidence that salamanders are not present at a given site. This information will be useful for developing guidelines for surveys to be conducted prior to commencement of ground-disturbing activities.

*Microclimate and Surface Activity*

To understand the environmental conditions that influence vertical (from below ground to surface) and horizontal (across the ground surface) salamander movements, we combined bi-weekly surveys of PIT-tagged salamanders on population demography plots, using enhanced detection technology (see further details below), with environmental monitoring by weather stations. Prior to initiating surveys, we installed HOBO weather stations (Figure 2) in each plot to record the ambient temperature, precipitation, and relative humidity just above ground level; soil temperature and moisture beneath one log and temperature within the center of the log; and soil temperature and moisture beneath one rock. Instrumented logs and rocks are of dimensions and types that are commonly used by salamanders. Weather stations were surrounded in hardware cloth and wiring was buried below ground to protect sensitive instruments from damage by rodents or other small animals. Weather stations were set to record measurements continuously every 30 minutes for the duration of the study.

Figure 2. HOBO weather station monitoring environmental variables in a Sacramento Mountain salamander (*A. hardii*) demography plot. Orange flagging indicates the location of an instrumented rock.

During bi-weekly visits to demography plots, the entire area of each plot was scanned for PIT-tagged salamanders using a PIT tag reader (Biomark HPR Plus) and antenna (Biomark BP Plus). The antenna permits detection of tagged salamanders beneath rocks, logs, and other cover objects and up to about 25 cm below ground (Figure 3). Upon detection of a PIT-tagged salamander, the reader emits a beep and the unique PIT tag code of the salamander is displayed on the screen. For salamander detections using the antenna, we recorded geographic coordinates at the point of detection and the cover object type associated with the detection.

Figure 3. Intern searching for PIT-tagged salamanders in and around cover objects. Orange flags show the previous survey's locations of a male and a female salamander detected within the log.

Following data collection in summer 2023, we will develop models relating the location of salamanders to aboveground microenvironmental characteristics and to soil moisture and thermal conditions. These models could then be used to provide important information that can guide the timing of forest management treatments relative to seasonal conditions, within-season weather events, and likely salamander activity patterns. Independent variables for this analysis may include precipitation amount, air temperature, relative humidity, and soil moisture and temperature at the surface and at varying depths below cover objects; all variables to be assessed at varying intervals preceding salamander detections and movements (e.g., in the preceding 24-, 48-, or 72-hrs). Model covariates will include variables that may influence aboveground microenvironments and soil moisture and thermal regimes, including topography (e.g., elevation, slope, and aspect), soil type, and forest structure and composition. Our data will also allow us to evaluate whether and how salamander cover objects (logs and rocks) respond to seasonal and event-scale weather, including whether cover objects of different types, conditions, and dimensions differentially retain moisture. This information is important for understanding how natural disturbances (e.g., wildfires and beetle outbreaks) and management treatments (e.g., thinning and prescribed fire) that affect the presence and characteristics of cover objects may influence salamander habitat, and is also critical for developing guidelines for restoration treatments that can include intentional provisioning of cover objects.

*Management Recommendations*
Upon completion of field work for this project in August 2023, we will summarize results in a way that informs land managers about the status of *A. hardii* in relation to conservation and habitat restoration needs.

**Results**

Project status and results are provided below for the primary tasks included in the project agreement during the 2023 fiscal year.

*Population Demography*
We detected 362 salamanders in demography plots during the 2022 field season. Of these, five were observed but escaped, preventing us from collecting comprehensive data on those individuals. For salamanders that were captured, 74% were new salamanders and 26% were previously marked, recaptured salamanders. In the 2022 field season, 14% of salamanders captured were females, 9% were males, and 77% were subadults or adults for which sex could not be determined.

In the White Mountains, we captured two new salamanders at Big Bear and 142 new salamanders at Ski Apache. In the Sacramento Mountains, we captured 88 new salamanders at Lightning Lake and 84 new salamanders at Russia Canyon.

Of 362 salamanders detected during demography surveys for which microhabitat data were collected, 54% were found under rocks, 36% were found under or within logs, 9% were found under bark, 1% (4 individuals) were observed on the forest floor, and one salamander was found beneath cow feces. Because of time constraints, we were unable to collect data on availability of cover object types around locations of salamander captures. Thus, we cannot make a comparison of use versus availability of cover objects.

*Impacts of Wildfire on Occupancy*
In 2022, we conducted 31 occupancy surveys at sites historically occupied by salamanders or sites that appeared to contain suitable habitat within the White and Sacramento Mountains. These included 17 surveys in unburned sites, two surveys in sites that had burned at low severity, and 12 surveys at sites that burned at moderate/high severity. Twenty-one of the 31 occupancy surveys were conducted at sites documented through Natural Heritage New Mexico data to have been historically occupied by *A. hardii*. We detected salamanders at 71% of sites that were historically occupied.

Of 109 salamanders captured in the White and Sacramento Mountain ranges during occupancy surveys and for which microhabitat data were collected, 71% were found under or within logs and 29% were found under rocks. Because of time constraints, we were unable to collect data on availability of cover object types around locations of salamander captures and thus cannot assess use versus availability of cover objects.

*Detection Probability*
After completion of the 2023 field season, we will use data collected from repeated surveys of demography plots to model detection probabilities for *A. hardii* and quantify the extent to which these probabilities differ among sites and between mountain ranges. We will use the detection probability estimates for each site to calculate how many surveys would be needed to determine, with 95% confidence, that salamanders are not present at a given site and thus would not likely to be impacted by proposed forest management activities.

*Microclimate and Surface Activity*
We scanned each demography plot three times for PIT-tagged salamanders. We detected one tagged salamander with the sweeping antenna at Big Bear, 26 salamanders at Ski Apache, 27 salamanders at Lightning Lake, and 25 salamanders at Russia Canyon.

We collected microclimate data from weather stations installed in demography plots continuously from 2021 to present. Microclimate data indicate daily and seasonal trends and variability in above- and belowground environments and differences in microenvironments associated with log vs. rock cover objects (Figure 4). These data will be used to relate microclimatic conditions to habitat characteristics and salamander demography as described above after data collection is complete.

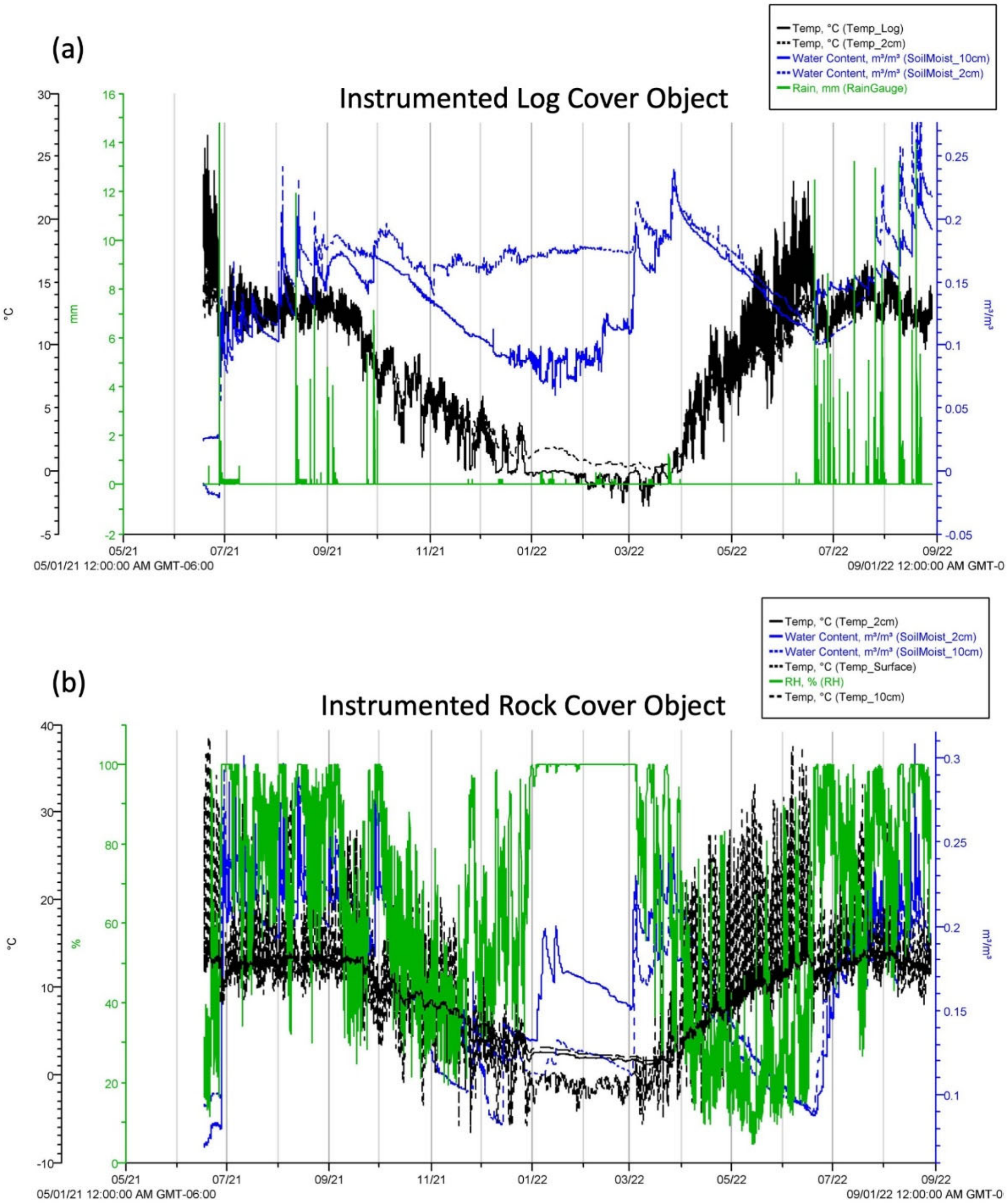


Figure 4. Above- and belowground microclimate for a log (a) and rock (b) cover object, for May 2021 through August 2022. Data are collected continuously at 30-minute intervals. For log cover objects, measurements include temperature (ºC) within the log cover object measured at center pith, temperature (ºC) 2cm below soil surface underneath the cover object, soil moisture ($m^3/m^3$) at 2cm and 10cm depths below soil surface and underneath the cover object, and surface rainfall (mm) beneath the forest canopy. For rock cover objects, measurements include soil temperature (ºC) and soil moisture ($m^3/m^3$) at 2cm and 10cm depths below soil surface and underneath the cover object and air temperature (ºC) and relative humidity (%) beneath the forest canopy.

*Management Recommendations*
We plan to summarize the results from all four tasks above to develop conservation guidelines and actions to inform the protection of remaining *A. hardii* populations and the restoration of habitats within their geographic range.

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