Energy Research and Development Division

FINAL PROJECT REPORT

Mitigating Impacts of Solar Energy Development on Desert Tortoises

Indoor Rearing and Release of Head-Started Desert Tortoises

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Mitigating Impacts of Solar Energy Development on Desert Tortoises: Indoor Rearing and Release of Head Started Desert Tortoises is the final report for the Use of Indoor Rearing for Head-Starting Desert Tortoises project (Contract Number: EPC-16-038) conducted by the University of California, Davis and Savannah River Ecology Lab. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

The Mojave desert tortoise (*Gopherus agassizii*) is a special-status species whose preservation often conflicts with land use in California's deserts. This is especially true given the rapid rise of utility-scale solar energy development in the southwestern deserts to meet targets for renewable energy production. Current laws and policies require that negative impacts to protected species like the desert tortoise be either minimized or offset by mitigation actions. Research is needed to identify the most effective mitigation tools for the desert tortoise as well as aid its recovery and streamline future permitting for renewable energy development.

Researchers from the University of California, Davis, and the University of Georgia Savannah River Ecology Laboratory released juvenile desert tortoises reared in captivity using different husbandry methods (head-starting) and for different durations to evaluate the potential value and role of indoor rearing as a way to increase the effectiveness of tortoise head-starting. Results showed that post-release tortoise survival increased with the size of the tortoises when released, regardless of whether they were reared exclusively outdoors or through a combination of indoor and outdoor rearing. Incorporating an indoor-rearing component greatly reduced the time required to produce large juveniles of releasable size with no observed negative effects on either survival or post-release movement behaviors. The observed combination of high survival and high site fidelity increases the likelihood that released tortoises would be recruited into target populations that need recovery.

By shortening the captivity period, indoor head-starting can dramatically reduce the costs of rearing tortoises and increase production of tortoises from head-starting facilities. These improvements facilitate wider implementation of head-starting as a recovery tool for desert tortoises. Implementing more cost-effective recovery actions such as indoor head-starting will also aid mitigations for solar energy development and should increase the probability of delisting the desert tortoise as a special-status species in the future.

Keywords: Desert tortoise, *Gopherus agassizii*, head-starting, husbandry, mitigation, movement, solar energy, survival, threatened species, wildlife

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EXECUTIVE SUMMARY

Introduction

Meeting the state's ambitious goals for renewable-resource energy production requires expanded development of solar-generation facilities. Without study and mitigation measures, however, solar-energy development can conflict with the state's equally ambitious commitment to protect California's natural resources and at-risk species. One such at-risk species often at the center of land-use conflict in California's deserts is the Mojave desert tortoise, *Gopherus agassizii*, which inhabits much of the desert landscape that is also well-suited for solar-energy facilities. Once relatively abundant across much of the Mojave Desert, desert tortoise populations have declined since the 1970s and are now officially threatened under California and United States endangered-species acts. Ongoing habitat loss, including losses to solar-energy development, has created the urgent need to design and refine strategies that support this species' recovery and eventual delisting as an endangered species. Recognizing this need, the *Revised Desert Tortoise Recovery Plan of the United States Fish and Wildlife Service* mandated development of protocols and guidelines to head-start tortoise populations as a means to increase their numbers.

Head-starting is rearing young tortoises in captivity to sizes where their chances of survival are increased when they are released into the wild. Biologists are optimistic that head-starting those young tortoises, when combined with other conservation measures, can increase wild desert-tortoise populations. Several studies have shown that rearing desert tortoises in captivity can increase the number of tortoises that are large enough for successful release into the wild. Given their slow rate of growth, however, head-starting desert tortoises with the existing method of rearing them in protected outdoor enclosures can require an investment of six to ten years or longer; this extended time frame and investment limits the feasibility of head-starting desert tortoises. Methods that reduce the cost and time required to produce head-started tortoises for release into the wild can broaden the portfolio of strategies to resolve conflicts with solar-energy development and improve desert tortoise survival rates.

Project Purpose

This project built on current successes to head-start desert tortoises in outdoor enclosures by evaluating indoor husbandry to further accelerate tortoise growth. This project also evaluated the role of tortoise size in increasing their survival rates after release into the wild, a measurable requirement for effectively augmenting or recovering declining tortoise populations. The overall project goal was to improve wildlife mitigation strategies for desert tortoises affected or displaced by renewable energy and other development.

Project Approach

This project was a collaboration of scientists from the University of California, Davis, and the University of Georgia's Savannah River Ecology Lab. Biologists and managers from the United States Fish and Wildlife Service, United States National Park Service, California Department of Fish and Wildlife, United States Geological Survey, and other scientists also consulted to guide the study's design, location, and permitting. The National Park Service–Mojave National Preserve provided additional logistical support.

Researchers obtained hatchling Mojave desert tortoises from females inside the Mojave National Preserve. Female tortoises were outfitted with radio transmitters, tracked, and X-rayed in the spring. When eggs were confirmed on X-ray images, females were brought to protected outdoor enclosures at the Ivanpah Desert Tortoise Research Facility where they laid their eggs before being returned to their points of capture. These nests incubated in the protected enclosures. When juvenile tortoises hatched in late summer, they were divided into two head-starting husbandry treatments. In the first treatment, hatchling tortoises were reared indoors for a year, then outdoors in enclosures for a second year. In the second treatment, hatchings were reared exclusively outdoors in protected enclosures for two years, with supplemental food and water from sprinklers. Older juvenile tortoises that had been reared exclusively outdoors in enclosures since 2011–2013 in an earlier study made up a third study group. Tortoise growth and survival rates, from the time of hatching, were measured annually for the duration of captivity and compared among the three groups when they were released into the wild.

After head-starting, tortoises from the two husbandry treatments and the third group were released inside the Mojave National Preserve where their mothers were originally found. All head-started tortoises were outfitted with small radio transmitters at release so that researchers could track them and determine their fates. Tortoises from the three groups were released in the fall of 2018 and 2019 and radio tracked in the wild until the fall of 2020. Survival and movement rates of tortoises from the three release groups were then compared. The data collected was used to evaluate the potential benefits of indoor rearing on the growth and survival of juvenile desert tortoises in captivity, and on their survival and behavior after release.

A technical advisory committee was formed to advise the project team. Committee members included desert tortoise researchers, representatives of public wildlife or regulatory agencies, and representatives of the solar-energy industry. The committee met twice and provided oversight and guidance on project procedures. No major project challenges or obstacles were identified.

Project Results

Growth rates of the tortoises reared indoors their first year were nearly 300 percent greater than those of tortoises reared exclusively outdoors. As a result, after two years of total head-starting, tortoises reared indoors their first year were nearly as large as those reared exclusively outdoors for six to seven years. They likewise had shells that were as hard as those of tortoises reared exclusively outdoors for six to seven years. Whether reared indoors their first year or exclusively outdoors, and regardless of whether they had been head-started for two years or seven, all tortoises head-started for the project were healthy when they were released.

Survival of head-started tortoises in captivity was consistently high regardless of the rearing treatment, although the first-year survival rate of tortoises reared indoors was 100 percent, compared with 91 percent for tortoises reared outdoors. The subsequent survival of all tortoises in outdoor enclosures after their first year ranged from 96 percent to 98 percent.

Size at release appeared to be the greatest determinant of survival in the wild. The tortoises reared exclusively outdoors for only two years averaged 83.7 millimeters in length when released in 2018 and had an annual survival rate of 68 percent their first year in the wild. In contrast, tortoises reared outdoors for 6 to 7 years or those reared indoors their first year averaged 49 percent and 40 percent greater in length, respectively, and both groups had annual first-year survival rates of about 20 percent higher. Annual survival of tortoises released in 2018 increased the second year and ranged from 95.8 percent to 100 percent regardless of their husbandry differences. Tortoises released in 2019 had annual survival rates of 87 percent to 89.5 percent regardless of size differences or prior husbandry. All annual survival rates for head-started tortoises released in this study exceeded the much lower 48 percent annual survival rate of wild juveniles estimated in an earlier study at the same site.

Movement rates appeared to be driven more by the age of the tortoises than by size or prior husbandry. Tortoises reared exclusively outdoors for 6 to 7 years had the highest movement rates and settled the farthest from their release locations compared with younger head-started tortoises. Tortoises reared indoors their first year had movements that were often intermediate in length to the other two release groups, and they often settled closest to their release locations. Tortoises reared exclusively outdoors for just two years before release had movements that were either among the smallest or similar to their same-aged but much larger siblings reared indoors their first year.

In sum, the results of this project support indoor rearing to accelerate the growth rates of desert tortoises in head-starting programs. Indoor husbandry produced tortoises that were as large as tortoises 6 to 7 years old reared exclusively outdoors. Due to their size advantage, tortoises reared indoors survived in the wild after release at rates on a par with older ones, and at rates higher than smaller, same-aged siblings reared exclusively outdoors. Tortoises produced using indoor rearing had movement behaviors similar to those of their same-aged siblings, and they settled closest to their release locations of all three release groups, suggesting that they would be good candidates to increase targeted populations where dispersal could be problematic.

While this project delivered key findings and insights that improve the feasibility of head-starting in tortoise population augmentation programs, several uncertainties and opportunities for additional work remain. Future research is needed to determine the longer-term fates of tortoises released from head-start programs. Although the present results are indeed encouraging, the ultimate goal of any population augmentation program is for released animals to enter the local populations and produce offspring of their own. This will require additional radio tracking or extensive mark-recapture efforts to ensure that head-started tortoises maintain these high levels of survival as they mature in the wild and reach reproductive maturity. Also, given the husbandry successes demonstrated in this project, it would be worth studying the outcome of head-starting tortoises for just one year indoors before release, with no additional captivity in outdoor enclosures for a second year. This further refinement would shrink the total investment of captive husbandry to just one year and remove the need for extensive, potentially costly irrigated outdoor enclosures.

Knowledge Transfer

Findings from this project have been disseminated in a variety of ways: meetings and discussions with key stakeholders, annual reports to permitting agencies, talks given at the annual symposia of the Desert Tortoise Council, articles and a short video in national newspapers like the *Washington Post*, and publications in peer-reviewed scientific journals. The technical advisory committee included several members of key stakeholder groups that further helped distribute study results to public and private partners.

These stakeholders included public resource and regulatory agencies (United States Fish and Wildlife Service, California Department of Fish and Wildlife), energy developers and other land developers, land managers (including the United States National Park Service and the United States Bureau of Land Management), environmental organizations, other scientists, and the general public. By demonstrating the feasibility and success of improved methods of head-starting desert tortoises, key stakeholders can make better-informed decisions about how best to offset the negative impacts of renewable energy development on this species. This can ultimately ease regulatory barriers like identifying suitable mitigation measures for planned development in desert tortoise habitat and increase the portfolio of conservation efforts available for recovery of this listed species.

Benefits to California

Sustainable development of solar energy capacity requires effective environmental mitigation. Mitigation tools to aid populations or minimize harm to at-risk species like California's iconic Mojave desert tortoise, like the tools developed in this project, are therefore critical to both Californians in general and the state's utility ratepayers. It is expected that improved head-starting methods for recovering tortoise populations in a timely fashion at reduced cost can help ease regulatory barriers that arise during planning of energy development in desert tortoise habitat. These improved methods should together decrease costs to ratepayers while increasing public acceptance of solar energy development. These successes can also guide future research into shortening the time required to produce healthy desert tortoises and increase their populations in the wild.

CHAPTER 1: Introduction

Background and Context

Meeting California's energy generation mandates in the 21st century requires the development and ecologically sustainable application of new and existing technologies. Industries are therefore either actively developing or planning large-scale renewable-resource generation facilities, including solar arrays in California's deserts. Both industry and public partners, however, recognize the need to also minimize impacts to biological systems, including threatened habitats and species. One opportunity to meet the goals of maximizing the ecological sustainability of energy projects, while minimizing their environmental costs is to develop or refine mitigation strategies that ensure the survival of special-status species.

The Mojave desert tortoise, *Gopherus agassizii*, is one special-status species often in conflict with land use in California's deserts (Conservation Biology Institute 2013). The Mojave desert tortoise, hereafter referred to as 'desert tortoise', is threatened under both state and federal endangered species acts. Population declines that began in the 1970s, which ultimately led to its listing in 1990, continued across much of its range, including in recent decades (Federal Register 1990; Allison and McLuckie 2018). Continuing desert tortoise population declines have been driven largely by ongoing habitat loss and increases in the numbers of predators like coyotes (*Canis latrans*) and common ravens (*Corvus corax*), whose populations are subsidized in exurban areas that have encroached into deserts (Boarman 2003). Juvenile tortoises in particular often fall prey to these predators. Additional mortality from these subsidized predators has further reduced the naturally low rates of juvenile tortoise survival in the wild (Hazard et al. 2015; Nagy et al. 2015b; Daly et al. 2019), which have been estimated at 48 percent (plus or minus 9 percent) at the location of the current study (Tuberville et al. 2019). These increasing threats to the Mojave desert tortoise have created the urgent need to find ways to halt and reverse their population decline. Recognizing this need, the *Revised Desert Tortoise Recovery Plan* prescribed the development of protocols and guidelines for implementing head-starting as a population augmentation tool (United States Fish and Wildlife Service [USFWS] 2011).

Head-starting—the rearing of young animals in captivity to sizes at which they are less vulnerable to predators—is a promising mechanism for recovering desert tortoise populations. Head-starting has increasingly been shown to be an important tool in turtle and tortoise conservation (Thompson et al. 2020), increasing populations while other conservation actions simultaneously address the ongoing causes of decline (Burke 2015). In general, the increased size and potentially harder shells of head-started turtles can decrease the risk of predation when compared with their smaller, wild counterparts. In desert tortoises, the associated increases in shell volume with size may also provide the additional benefit of greater bladder water storage, reducing the risk of desiccation (Jørgensen 1998). There are, therefore, potentially two mechanisms by which head-starting can increase juvenile survival: through a lower risk of death from predation and from desiccation. Population models suggest that successful captive-rearing programs that produce large cohorts can "boost" populations

(Heppell et al. 1996), and in fact may eventually be required along with other conservation actions to prevent the complete loss of desert tortoise populations (Spencer et al. 2017).

Several studies have successfully reared desert tortoises in captivity for use in head-starting programs. Morafka et al. (1997) were first to show that desert tortoises could be successfully reared in predator-proof outdoor enclosures. Survival of juvenile tortoises in captivity in predator-proof outdoor enclosures is much higher than in the wild, sometimes nearly doubling annual survival rates (Nagy et al. 2015a; Tuberville et al. 2019). Nagy et al. (2015a) also found that adding rain to outdoor enclosures with irrigation sprinklers could increase the growth of neonates and older juvenile tortoises and was particularly important for the survival of older juveniles during drought years. However, survival of tortoises later released in the wild was still quite low if they were released while still small (Nagy et al. 2015a). Based on these findings, Nagy et al. (2015a) recommended providing added water in the form of this "supplemental rainfall" in head-start enclosures and delaying release of the tortoises until they were larger. In related work, Nagy et al. (2015b) released juvenile desert tortoises that had been head-started for 2–15 years and found that post-release survival increased with the size of the released tortoises, leading them to propose a minimum release size of 100 millimeters (mm) midline carapace length (MCL).

One challenge that desert tortoise head-starting programs face is the considerable investment of time and resources required to rear tortoises to sizes large enough for successful release into the wild. Juvenile tortoises can take up to nine years to reach 100 mm MCL, both in the wild and with supplemental rainfall in outdoor enclosures (Nagy et al. 2015b; Nagy et al. 2020). Although using supplemental rainfall can increase tortoise growth rates in outdoor enclosures, it still requires up to six years of captive rearing for tortoises to reach releasable sizes when reared in outdoor enclosures from hatching (Tuberville et al. 2019). The development of head-starting methods that could shorten this timeline could therefore greatly improve the feasibility and effectiveness of this recovery tool and its potential for use as a mitigation strategy.

One prospect for shortening the time it takes for desert tortoises to reach 100 mm MCL during head-starting is to rear them indoors for at least some part of their early years. Daly et al. (2019) showed in a pilot study, for example, that just eight months of indoor husbandry after hatching greatly accelerated tortoise growth rates relative to those reared in either outdoor enclosures alone or those ranging free in the wild after hatching. The accelerated indoor growth rate was likely due to tortoises remaining active over their first winter instead of hibernating, and to the supplemental food they received indoors. Ultimately, however, the development of a husbandry method that shortens the time it takes to produce head-started desert tortoises to 100 mm MCL is not, on its own, sufficient to demonstrate its value as a recovery tool. Tortoises produced from any head-starting method should have a high survival rate after release into the wild, and they should show similar movement behaviors and the ability to "settle" into their habitats when released into the wild. The primary goal of the present study is to evaluate both the use of indoor husbandry and its impact on survival and movement behaviors of the tortoises after release into the wild.

Objectives

The two primary objectives of the present project were to:

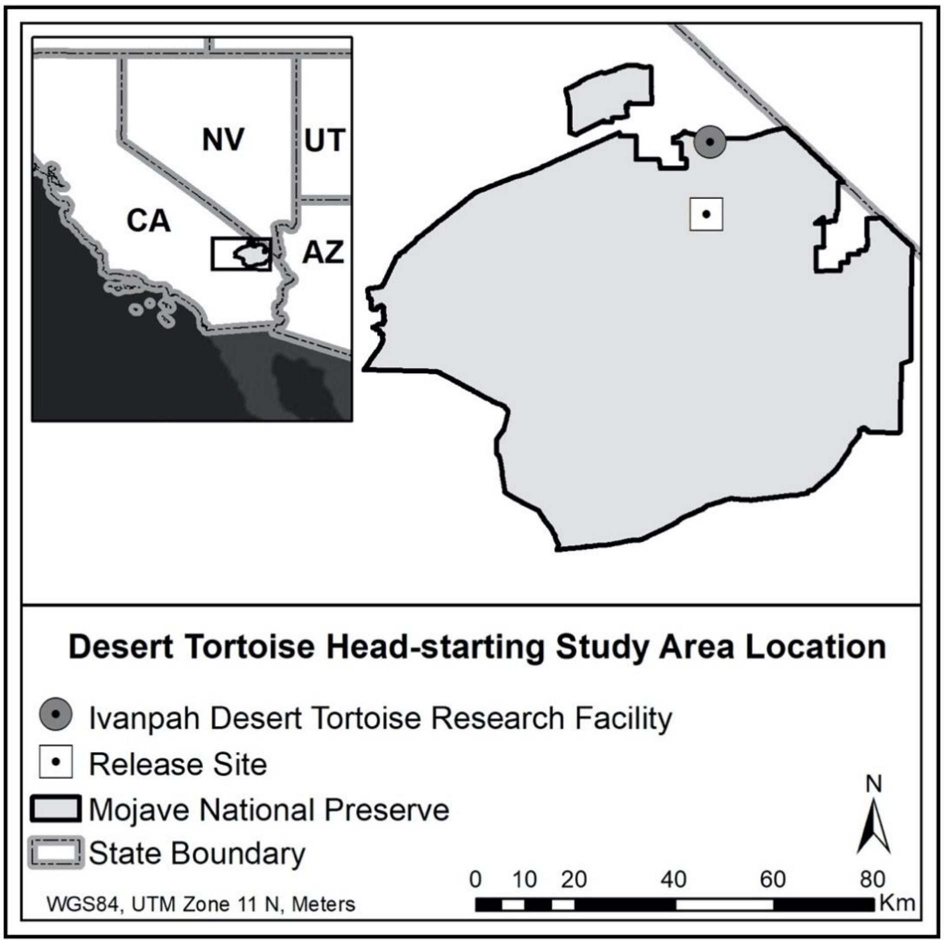
1. Evaluate the benefits and the unintended consequences of indoor head-starting by comparing growth, body condition, and the post-release behavior and survival of indoor-head-started and outdoor-head-started desert tortoises.
2. Evaluate the relationship between size and survival of juvenile desert tortoises released into the wild.

CHAPTER 2: Head-Starting Methods

Study Site

The research was conducted in the southern part of Ivanpah Valley in the Mojave National Preserve in San Bernardino County, California (Figure 1). This area lies in the Eastern Mojave recovery unit in the Ivanpah Critical Habitat Unit for the Mojave desert tortoise, as delineated in the revised recovery plan (USFWS 2011). All desert tortoise husbandry was conducted at the Ivanpah Desert Tortoise Research Facility (IDTRF, Figure 2). All field work on the project, including releases of head-started tortoises, was conducted approximately 10 kilometers (km) south-southwest of the facility and inside the Mojave National Preserve.

Figure 1: Location of Study Site



Location of the study site for the present study in the Ivanpah Valley of the Mojave National Preserve, California, USA.

Source: Jacob A. Daly, University of Georgia

Figure 2: Ivanpah Desert Tortoise Research Facility

All indoor husbandry was performed inside the facility.

Photo credit: Brian D. Todd, University of California, Davis

Obtaining Juvenile Tortoises

Hatchlings were obtained for the study by capturing and radio tagging wild female tortoises, including as early as April 2011 as part of previous projects. When a female tortoise was found and added to the study, it was outfitted with Very High Frequency (VHF) radio transmitters so it could be radio tracked and monitored. Females were tracked weekly to monthly to monitor their welfare and reproductive status. Radio transmitters were replaced every two years as batteries neared expiration. Females were occasionally removed from the study and new ones added over time, but no more than 30 females were radio tagged at any one time.

Each female tortoise was x-rayed (Diagnostic Imaging Systems: Poskam, Colorado; 60 kilovoltage peak, 0.8 milli-ampere-second, 74 cm focal length) every 10–14 days from mid-April through mid-May when they were most likely to produce their first clutch of eggs (Figure 3). When calcified eggs were visible on an x-ray for a female (Gibbons and Greene 1979), the female was placed into one of 30 outdoor, predator-proof nesting pens at the IDTRF (Figure 4). Each pen included adequate shelter from temperatures via artificial burrows and natural shrub cover. Females were allowed up to 30 days to lay their eggs in the pens. Females that nested were returned immediately to their last burrow location in the wild; females that did not nest within 30 days were released back at their last burrow location without having nested.

Figure 3: Radiograph of Female With Eggs

An x-ray showing a female Mojave desert tortoise with six calcified eggs ready to be laid. Also visible is an externally attached radio transmitter with a trailing antenna shown at top of image, and a temperature logger affixed externally to the shell at the top right of the image.

Photo credit: Tracey D. Tuberville, Savannah River Ecology Laboratory

Figure 4: Female Tortoise in Nesting Pen

The female in Figure 3 who had calcified eggs visible on an x-ray was placed in a nesting pen to lay her eggs. Females were kept for up to 30 days to allow them to nest; nesting was confirmed by x-raying the females every 10–14 days. Females were returned to the wild at their point of capture after they had either nested or 30 days had passed.

Photo credit: Brian D. Todd, University of California, Davis

Nests were left to incubate where they were laid in the pens. Beginning in August through September each year, approximately 80 days after estimated nesting dates, all pens were searched several times daily for any emerging hatchlings. Any hatchlings that were found were removed, and immediately weighed (to nearest 0.1 g) and measured (mid-line carapace length, MCL [mm] to nearest 0.1 mm; Figure 5). Each hatchling was individually marked by notching unique combinations of marginal scutes with nail clippers using the 1-2-4-7 coding system and codes assigned by USFWS (Cagle 1939). Finally, nesting pens were searched for any unhatched eggs or unemerged hatchlings. Hatchlings were obtained in this manner for use in the present study in 2011, 2012, 2013, 2016, and 2017.

Figure 5: Measuring a Hatchling Tortoise

An example of a hatchling tortoise having its midline carapace length measured with calipers. Temporary markings like those visible in this photograph were made using non-toxic inks and removed before tortoises were released.

Photo credit: Brian D. Todd, University of California, Davis

Head-Starting Treatments and Husbandry

Tortoises were reared after hatching in one of two husbandry treatments; siblings from a clutch were divided across the different treatments. For one treatment, tortoises were placed directly into predator-proof, outdoor enclosures for the entirety of their captivity before they were released; this will be referred to this as the 'Outdoor HS' treatment. For the second treatment, tortoises were reared indoors their first year after hatching and then moved into predator-proof outdoor enclosures for their second year; this will be referred to as the 'Combo HS' treatment.

In September of all years, the newest cohort of outdoor HS tortoises was placed into predator-proof, outdoor enclosures for the entirety of their husbandry prior to release. All enclosures measured approximately 30 x 30 meters (m) and were constructed of chain-link fence walls with an outer perimeter of corrugated metal along the base that extended 1 m into the ground to exclude terrestrial predators. The enclosures were completely covered by mesh netting to exclude aerial predators, including ravens and any birds of prey (Morafka et al. 1997; Figure 6). Enclosures were subdivided with sheet metal into smaller pens and equipped with manually operated sprinkler systems fed by an underground aquifer. Each of the two juvenile rearing enclosures was subdivided into 9 pens measuring 10 x 10 m. Enclosures contained native vegetation and natural cover (e.g., creosote, rocks, downed yucca logs), and thus reflected habitat outside the enclosures. Natural cover was supplemented with artificial burrows created from 53-centimeter (cm) length, 10-cm-diameter perforated plastic pipes, or from 1 m length, 30.5-cm diameter cardboard tubes (concrete form casings, "sonotubes"), cut in half longitudinally and placed at 30-degree angles, then buried underground (Figure 7). Tortoises were distributed among enclosures as equally as possible each year among several of the subdivided pens with a maximum density of approximately one individual per 10 square m (6–7 individuals per pen in 2011, 10 individuals in 2012, and 10–11 individuals in 2013). No more than two siblings from each clutch were assigned to the same subdivided pen.

Figure 6: Outdoor Enclosures With Mesh Netting

This photo shows the mesh netting used in all outdoor enclosures to protect the tortoises from aerial predators like common ravens and birds of prey.

Photo credit: Brian D. Todd, University of California, Davis

Figure 7: Burrow in Female Nesting Pen

This photo shows a burrow for a female desert tortoise ready to lay her eggs in one of the nesting pens. Females usually laid their eggs in the completed burrows or dug their own.

Photo credit: Kurt A. Buhlmann, Savannah River Ecology Laboratory

All tortoises in outdoor enclosures were provided with "supplemental rainfall" using the sprinklers shown in Figure 8. Based on the sprinkler flow rates, an estimated 4.5-9 cm of supplemental rainfall were added annually. Sprinklers were timed to follow typical rainfall patterns in this part of the Mojave, where monsoonal summer rains occur, but where winter rainfall is still dominant (Beatley 1974; Nafus et al. 2017b). The additional simulated rain was intended to support the germination and growth of annual plants on which the juvenile tortoises forage, as well as to keep hatchlings hydrated so they could forage on dry plants they might otherwise have avoided. Hatchlings often emerge from their burrows to forage and drink when it rains; the water that tortoises gain during rainfall is important for nutrient balance and digestion efficiency (Nagy and Medica 1986; Peterson 1996; Oftedal 2002).

Figure 8: Water Sprinklers in a Pen

Water sprinklers shown in this photo were used to both encourage growth of native vegetation for the diet of captive desert tortoises and to allow the tortoises to drink.

Photo credit: Kurt A. Buhlmann, Savannah River Ecology Laboratory

Tortoises in outdoor enclosures had access to native plants to forage, including blond psyllium (*Plantago ovata*), desert dandelion (*Malacothrix glabrata*), Booth's evening primrose (*Eremothera boothii*), and desert globemallow (*Sphaeralcea ambigua*) (Jennings and Berry 2015; Nafus et al. 2017b). Supplemental feeding of all tortoises in outdoor enclosures also began in March 2016 (Figure 9). Tortoises were fed a mixture of leafy greens and water-soaked Mazuri® Tortoise Diet (Mazuri Exotic Animal Nutrition, St. Louis, Missouri). The greens included dandelion (*Taraxacum officinale*), mustard greens (*Brassica juncea*), turnip greens (*Brassica rapa*), collards (a cultivar of *Brassica oleracea*), endive (*Cichorium endivia*), and escarole (*C. endivia latifolia*). The weekly combination of greens varied by availability but always consisted of at least three different types in an attempt to approximate the nutritional properties of the desert tortoise's natural diet (Jarchow et al. 2002).

Figure 9: Feeding Tortoises in Outdoor Enclosures

Feeding day for tortoises in a predator-proof outdoor enclosure. Food was placed on buried paving bricks or on new paper plates at each feeding to keep food off of the sand. The temporary colored spots allowed researchers to identify each tortoise without handling them. Colored markings were removed before a tortoise was released into the wild.

Photo credit: Kurt A. Buhlmann, Savannah River Ecology Laboratory

In September 2016 and 2017, in addition to placing newly hatched Outdoor HS tortoises into outdoor enclosures, several sibling Combo HS tortoises were placed in mesocosms inside the climate-controlled IDTRF for their first year of husbandry. Ambient temperature inside the IDTRF was maintained at approximately 24° Celsius (C). Mesocosms were made using 50-gallon (189 liter [L]) Rubbermaid stock tanks (132 x 79 x 30.5 cm) filled with a layer of natural desert sand as substrate (Figure 10). Six tanks were used, each housing five tortoises. Mini Combo Deep Dome Dual Lamp Fixtures (ZooMed Laboratories Inc., San Luis Obispo, California) were suspended over the tanks, each containing a 50-watt ZooMed Repti Basking Spot Lamp bulb for daytime basking and a ZooMed 50-watt Infrared Basking Spot bulb for night-time heat (Figure 11). The lights were connected to automatic timers; the basking lights were timed to operate from 0600–1830, and the infrared lights were timed to operate between 1900–0530. The lights created basking spots of 37°C during the day and 32°C at night. Each tank also had a 26-watt Exo-Terra Reptile UVB150 bulb (45 cm above substrate; Rolf C. Hagen Corp., Mansfield, Massachusetts) for optimal calcium metabolism and Vitamin D3 conversion; these UVB150 bulbs were timed for a 12h:12h light:dark cycle over the entire year of indoor husbandry.

Figure 10: Stock Tanks Used for Indoor Husbandry

The stock tanks pictured in this photo were used for rearing some tortoises indoors for one year after hatching. Each tank housed five newly hatched tortoises.

Photo credit: Kurt A. Buhlmann, Savannah River Ecology Laboratory

Figure 11: Lighting Setup Used for Indoor Husbandry

The dual-light fixture contained one daytime and one nighttime basking bulb to aid tortoises in regulating their temperatures for digestion and other activities. The uppermost lighting fixture contained a UVB bulb to aid in calcium and Vitamin D3 absorption.

Photo credit: Kurt A. Buhlmann, Savannah River Ecology Laboratory

Each indoor mesocosm tank included three hides constructed from halved plastic pipe (11.5 cm in diameter and cut into 12-cm linear segments) (Figure 12), and a paper plate that was used at feeding and replaced with a new one at each feeding. Because inadequate humidity has been linked to “pyramiding” of the shell as tortoises grow (Wiesner and Iben 2003), a humid hide box was provided in each mesocosm to promote smooth shell growth (Figure 13). Humidity was maintained in the hides by cutting a burrow-shaped entrance hole into plastic tote boxes (40 x 26 x 18 cm) and lining each tote box with approximately 7 cm of moist peat moss, which was re-moistened with a spray bottle every 3-4 days.

Figure 12: Hides in an Indoor Husbandry Tank

Example hides used in indoor husbandry tanks to allow tortoises to regulate their temperatures while feeling safe.

Photo credit: Kurt A. Buhlmann, Savannah River Ecology Laboratory

Figure 13: Humid Hide Box in Indoor Husbandry Tank

A humid hide box was provided in each indoor husbandry tank and used frequently by the captive tortoises.

Photo credit: Kurt A. Buhlmann, Savannah River Ecology Laboratory

Tortoises indoors were fed ad libitum 4-5 times per week during the indoor rearing period, using the same diet previously described for the Outdoor HS treatment. Twice weekly, their food was supplemented with a light dusting of Rep-Cal Calcium with Vitamin D3 (Rep-Cal Research Labs, Los Gatos, California). Combo HS tortoises were soaked for 15-30 minutes in 1-2 cm of water weekly. After one year of indoor husbandry, all Combo HS tortoises were moved outdoors into a 10 x 30-m predator-proof enclosure at the IDTRF for their second year of rearing. These larger enclosures contained all of the previously mentioned enclosure components (refugia, natural vegetation, sprinklers), and resulted in tortoises reared at a similar density (0.11 tortoises/m2) as the Outdoor HS-treatment tortoises.

All tortoises were reared using the methods described until they were released into the wild.

CHAPTER 3: Growth and Survival of Captive Tortoises

Data Collection for Growth and Survival of Captive Tortoises

The midline carapace length (MCL) and mass of each tortoise were measured upon hatching in late summer (August–September) in each year that hatchlings were obtained for the study. All captive tortoises were then measured and reweighed semi-annually. Combo HS tortoises were easily found in their indoor mesocosms and also measured. To find and measure the Outdoor HS tortoises, the outdoor pens were searched extensively while the sprinklers were on, which mimics rainfall and encourages tortoises to emerge from underground burrows and become active on the surface where they are more easily seen and found. All tortoises were returned to their mesocosms or outdoor pens after semi-annual measuring, except when tortoises were randomly selected for release into the wild to determine their fates after head-starting in September 2018 and 2019 (described in more detail in Chapter 4).

Mass was recorded to the nearest 0.1 gram (g) (Model HH320, OHAUS Corporation, Parsippany, New Jersey); when tortoise mass exceeded 300 g, the mass was recorded to the nearest 1 g (My Weigh 6001, HBI Technologies, Phoenix, Arizona). Dial calipers (Series 505, Mitutoyo, Aurora, Illinois) were used to record MCL, maximum shell height, and maximum shell width on the bridge, to the nearest 0.1 mm.

Tortoise body condition was calculated using the formula described in Nagy et al. (2002):

$$Body\ condition\ \left(\frac{g}{cm^3}\right) = \frac{weight\ (g)}{shell\ volume\ (cm^3)}$$

$$Shell\ volume\ (cm^3) = MCL(cm)\ \times\ width(cm)\ \times\ height(cm)$$

To calculate a shell hardness index (SHI), a 4-inch (10.2 cm) tension-calibrated micrometer (L.S. Starrett Company, Athol, Massachusetts, USA; model: 3732XFL-4) was first used to measure each tortoise’s uncompressed shell height (UCSH) at the center of the third vertebral scute (Nagy et al. 2011). Compressed shell height (CSH) was then measured by turning the micrometer spindle and compressing each tortoise’s shell between the two measuring faces until the spindle ratchet slipped continually for approximately 270 degrees (Daly et al. 2018). These measurements were used to calculate a shell hardness index described by Nagy et al. (2011), in which a SHI value of 100 corresponds to maximum hardness (i.e., an incompressible shell):

$$Shell\ Hardness\ Index\ (SHI) = \frac{CSH}{UCSH}\ \times\ 100$$

Program R (R Core Team 2017) was used for statistical tests and significance was assessed at alpha = 0.05. Data are presented as group means, plus or minus (±) 1 Standard Error (SE). Model residuals were visually inspected, and Shapiro-Wilk tests were used to test model assumptions of normally distributed residuals.

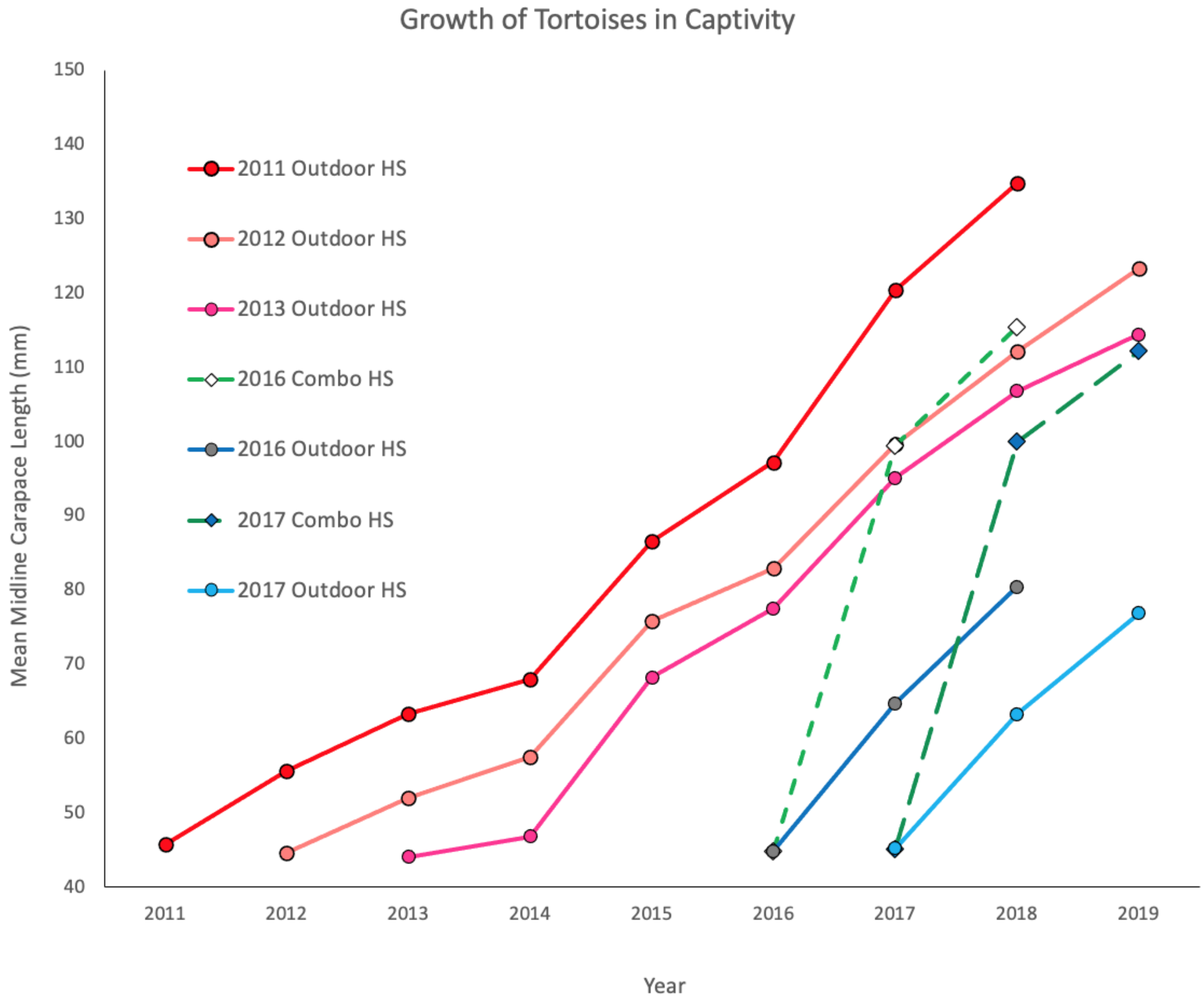
Linear mixed effects models (LME; ‘nlme’ package, ‘lme’ function) were used to compare MCL, mass, body condition, and shell hardness (shell hardness index, SHI) at the time of release among older Outdoor HS, Combo HS, and younger Outdoor HS groups for each of the two years when tortoises were released, 2018 and 2019. Maternal identification was included as a random effect in all models to account for possible maternal effects (Steyermark and Spotila 2001; Nafus et al. 2015b). MCL was included as a continuous covariate in models testing the effects of treatment on SHI, allowing an evaluation of whether treatments varied at similar sizes. An interaction between MCL and SHI was also tested. In any model in which the interaction was not significant, MCL was retained as a covariate, but the uninformative interactive term was removed from the final model.

Growth and Survival of Captive Tortoises Results

Growth Rates in Husbandry Treatments

Outdoor HS tortoises grew an average of 10.5±0.3 mm/year until Spring 2016, when supplemental feeding and watering began in outdoor enclosures. Outdoor HS tortoises then grew an average of 14.5±0.3 mm/year with the addition of supplemental feeding. Combo HS tortoises grew an average of 54.8±1.3 mm/year their first year indoors, and 13.4±0.5 mm/year over their second year, which was spent in outdoor enclosures. As a result, growth rates were much higher when tortoises were reared indoors than outdoors, with Combo HS tortoises growing more quickly over their combined two years of rearing than Outdoor HS tortoises over two years (Figure 14 and Figure 15).

Figure 14: Growth of Tortoises in Captivity Before Release



Plots of mean midline-carapace length for all tortoises in captivity prior to release in September 2018 or September 2019. Supplemental feeding of all Outdoor HS tortoises began in Spring 2016. The highest growth rates of head-started tortoises occurred for Combo HS tortoises (shown with the dash lines in the first year when they were reared indoors.

Source: Summary statistics and calculations provided by Susanna Mann, Collin J. Richter, and Brian D. Todd, University of California, Davis

Figure 15: Size Comparison Photograph of Head-Started Tortoises

Photographed from left to right: a newly hatched Mojave desert tortoise in September 2017, a one-year-old tortoise from the 2016 Outdoor HS group that had been reared outdoors for one year in a predator-proof enclosure, and a one-year-old tortoise from the 2016 Combo HS group reared indoors for one year.

Size Differences Among Release Groups

As shown in Table 1, older Outdoor HS tortoises and 2016 Combo HS tortoises were similar in size upon release in September 2018 despite their age differences, and both were significantly larger than the 2016 Outdoor HS tortoises at release. Older Outdoor HS tortoises were the heaviest upon release in 2018, followed by 2016 Combo HS tortoises, with 2016 Outdoor HS tortoises the lightest. Nevertheless, body condition did not vary significantly at release in 2018 among the three release groups. Older Outdoor HS tortoises and 2016 Combo HS both had harder shells than the 2016 Outdoor HS tortoises at release in 2018.

Table 1: Sizes of Tortoises in Release Groups

	Midline Carapace Length (mm)	Mass (g)	Body Condition (g/cm^3)	Shell Hardness Index
2018 Release				
Older Outdoor HS	125.0 (±2.4)[a]	370.0 (±19.0)[a]	0.57 (±0.01)	98.1 (±0.2)[a]
2016 Combo HS	117.2 (±2.0)[a]	300.6 (±14.3)[b]	0.57 (±0.01)	97.8 (±0.2)[a]
2016 Outdoor HS	83.7 (±1.3)[b]	115.9 (±5.0)[c]	0.57 (±0.01)	95.0 (±0.2)[b]
P-value	**<0.001**	**<0.001**	0.67	**<0.001**
2019 Release				
Older Outdoor HS	119.6 (±3.1)[a]	317.3 (±21.9)[a]	0.55 (±0.01)	85.3 (±3.1)[a]
2017 Combo HS	113.1 (±1.9)[a]	262.9 (±12.8)[b]	0.56 (±.01)	86.7 (±1.1)[a]
2017 Outdoor HS	79.8 (±1.1)[b]	99.6 (±3.9)[c]	0.55 (±.01)	58.1 (±3.9)[b]
P-value	**<0.001**	**<0.001**	0.24	**<0.001**

Comparison of size metrics for tortoises from each of three release groups in 2018 and 2019. Outdoor HS tortoises were raised entirely outdoors (6-7 years for Older Outdoor HS tortoises) and Combo HS were raised indoors their first year then outdoors their second year. Values shown are means (± 1 Standard Error). Superscript letters show pair-wise comparisons from post-hoc tests and differentiate groups that differ significantly at the alpha = 0.05 level.

Source: Summary statistics and calculations provided by Collin J. Richter (University of California, Davis) and Carmen M. Candal (University of Georgia)

The results of size comparisons among the tortoises at release in 2019 were similar to those released in 2018. Older Outdoor HS tortoises and 2017 Combo HS tortoises were similar in size upon release in September 2019 despite their age difference, and both were significantly larger than the 2017 Outdoor HS tortoises at release (Table 1). Older Outdoor HS tortoises were the heaviest upon release in 2019, followed by 2017 Combo HS tortoises, with 2017 Outdoor HS tortoises being the lightest. Nevertheless, body condition did not vary significantly at release in 2019 among the three release groups. Older Outdoor HS tortoises and 2017 Combo HS both had harder shells than the 2017 Outdoor HS tortoises at release in 2019.

Survival in Husbandry Treatments

Combo HS tortoises had higher rates of annual survival than did Outdoor HS tortoises, especially in the first year, when Combo HS tortoises were raised indoors (Table 2).

Table 2: Survival of Tortoises in Husbandry Treatments

	Annual Survival First Year of Head-Starting	Annual Survival Subsequent Years of Head-Starting
Outdoor HS	91%	96%
Combo HS	100%	98%

Comparison of annual survival for tortoises raised either solely outdoors (Outdoor HS) or those raised indoors their first year and outdoors their second year (Combo HS).

Source: Summary statistics provided by Brian D. Todd, University of California, Davis

Growth and Survival of Captive Tortoises Discussion

One of the greatest challenges in rearing desert tortoises in head-starting programs is timeliness. Desert tortoises exhibiting natural growth rates in the wild can take up to a decade to reach 100 mm MCL (Turner et al. 1987; Curtin et al. 2009)—the size recommended for release because survival rates are sufficiently high (Nagy et al. 2015b). Even the addition of supplemental rainfall to outdoor enclosures may reduce this period by only a few years, requiring as much as 6-9 years of captive rearing for tortoises to reach 100 mm MCL (Tuberville et al. 2019; Nagy et al. 2020). While tortoises remain under captive care, they require continued husbandry ranging from seeding native plants each year, to supplemental feeding, applying scarce water to enclosures, and continuous attention to outdoor enclosures to prevent their disrepair, which could allow ingress by predators that could be catastrophic to captive juvenile tortoises. The refinement of husbandry strategies that measurably shorten the time required to rear tortoises to larger sizes would therefore make head-starting a more feasible, less costly option. Having a feasible and inexpensive means of rearing tortoises makes head-starting more likely to become an effective tool for population recovery in the toolkit of conservation actions.

Two modifications proved useful in increasing growth rates of captive desert tortoises. First, the addition of supplemental feeding in outdoor enclosures in Spring 2016 increased growth rates by 38 percent when compared with prior years. This brought tortoise growth rates from 10.5 mm/year up to 14.5 mm/year—the higher end of what free-ranging tortoises can achieve in good years in wetter parts of the Mojave Desert (cf. Figure 7 in Nagy et al. 2020). The second husbandry modification that increased growth rates was indoor head-starting for the first year after hatching. While indoors, tortoises were fed frequently and did not hibernate for the several months of winter when temperatures drop too low to support much feeding, growth, or activity outdoors. As a result, growth rates of Combo HS tortoises were nearly 300 percent greater than those of Outdoor HS tortoises in their first year (54.8 mm/year compared with 14.5 mm/year). Consequently, Combo HS tortoises reached or surpassed the targeted size of 100 mm MCL by the end of their first year, without requiring an additional year of husbandry. Once Combo HS tortoises were moved outdoors after their single year of indoor rearing, their growth rates dropped to match those of Outdoor HS tortoises, which were exclusively reared outdoors. Nevertheless, the advantage of larger size from the first year of husbandry indoors had been accomplished.

The result of the high-growth rates in the one year of indoor husbandry meant that Combo HS tortoises at release were similar in length to Outdoor HS tortoises that were 4-5 years older, though they weighed slightly less. The Combo HS tortoises likewise had shells of similar hardness to Outdoor HS tortoises that were 4-5 years older. In contrast, Outdoor HS tortoises from the same clutches as the Combo HS tortoises were much smaller, weighed less, and had more pliable shells after an equal amount of husbandry time of 2 years; the main difference, again, was that they were reared in outdoor enclosures for the entirety of their 2 years, while Combo HS tortoises were raised indoors their first year and showed massive growth.

Reassuringly, tortoises from all three release groups had similar body-condition measures despite varying lengths of captive husbandry, two different rearing methods, and various sizes of tortoises (depending on which method was used and for how long the tortoises were reared). The body-condition measures reported here of around 0.55–0.57 g/cm^3 correspond to healthy or normal hydration and nutrition levels and were close to the >0.60 g/cm^3 threshold of prime body condition established by Nagy et al. (2002). Prime body condition may have been expected after captive rearing given the addition of supplemental food and water that the head-started tortoises received. However, the body condition measures were obtained in September and it has been shown that desert tortoises often emerge from their summer dormancy weighing less than they did the previous spring (Nagy and Medica 1986). The methods used here therefore appear to have produced appreciably healthy and vital head-started tortoises.

Head-starting with either Outdoor HS or Combo HS husbandry resulted in annual survival rates of 91-100 percent in captivity, much greater than the annual survival rates of similar-sized tortoises in the wild. For instance, annual survival rates of recently hatched tortoises over their first few years of life in the same area as the present study were estimated at 48±9 percent (Tuberville et al. 2019). A study of other parts of the Mojave Desert estimated an overall first-year post-release survival of 68 percent for juveniles aged 0.5-4 years, some of which had some prior captive husbandry (Nafus et al. 2017a).

That survival is greater in captivity is to be expected given that the tortoises were protected from predators and had access to food and water that can be scarce in the wild. What is more noteworthy is that rearing tortoises indoors resulted in 100 percent survival compared with just 91 percent annual survival in the first year for Outdoor HS tortoises. And, although survival dropped from 100 percent to 98 percent for Combo HS tortoises when they were moved outdoors their second year, they still had higher survival than did Outdoor HS tortoises over their subsequent years (98 versus 96 percent). The higher survival of Combo HS tortoises outdoors is likely a consequence of their much larger size after one year of substantial growth indoors. Ultimately, it appears that rearing tortoises indoors for their first year after hatching is a substantial refinement to head-starting protocols and results in large, healthy tortoises with high rates of survival in captivity before release. To be an effective mitigation or population augmentation strategy, however, head-starting desert tortoises must also translate into high post-release survival in the wild.

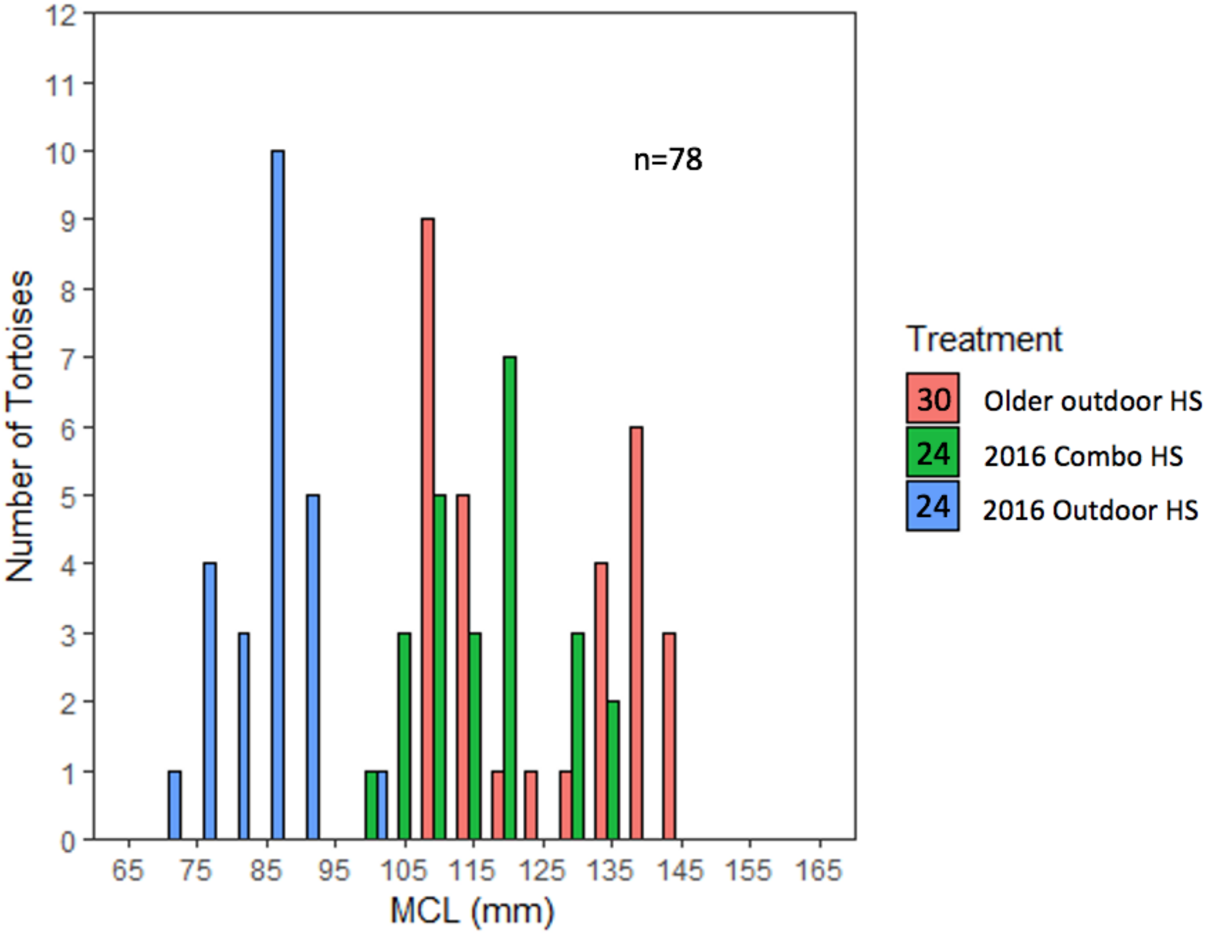
CHAPTER 4:
Post-Release Survival of Head-Started Tortoises

Assessing Post-Release Survival of Head-Started Tortoises

Two husbandry-rearing treatments were used to evaluate movements— Outdoor HS tortoises raised entirely outdoors and Combo HS that spent their first year indoors before moving into outdoor enclosures for their second year. Because many of the Outdoor HS tortoises had been reared since 2011–2013, they reached large sizes with extended outdoor husbandry. There were, therefore, effectively three groups of tortoises available for release and subsequent study of their survival and movements after head-starting: (1) older Outdoor HS tortoises reared entirely outdoors in predator-proof pens after hatching in 2011–2013, (2) Combo HS tortoises hatched in 2016 and 2017 that spent their first year indoors and their second year in outdoor pens, and (3) Outdoor HS tortoises that hatched in 2016 and 2017 and spent two years in outdoor pens. The older Outdoor HS tortoises from 2011–2013 were similar in size to the 2016 and 2017 Combo HS tortoises despite their greater age since Combo HS tortoises grew significantly during their first year indoors (discussed in Chapter 3). The increased growth rates of the Combo HS tortoises made them much larger than their same-aged Outdoor HS siblings from clutches that were split between the Combo and Outdoor husbandry treatments when they hatched in 2016 and 2017.

Releases in September 2018 included 30 older Outdoor HS tortoises that hatched in 2011 and 2012, 24 Combo HS tortoises that hatched in 2016, and 24 Outdoor HS tortoises that hatched in 2016. The size distribution of head-started tortoises released in September 2018 is shown in Figure 16. Releases in September 2019 included 24 older Outdoor HS tortoises that hatched in 2012 and 2013, 24 Combo HS tortoises that hatched in 2017, and 24 Outdoor HS tortoises that hatched in 2017. The size distribution of head-started tortoises released in September 2019 is shown in Figure 17.

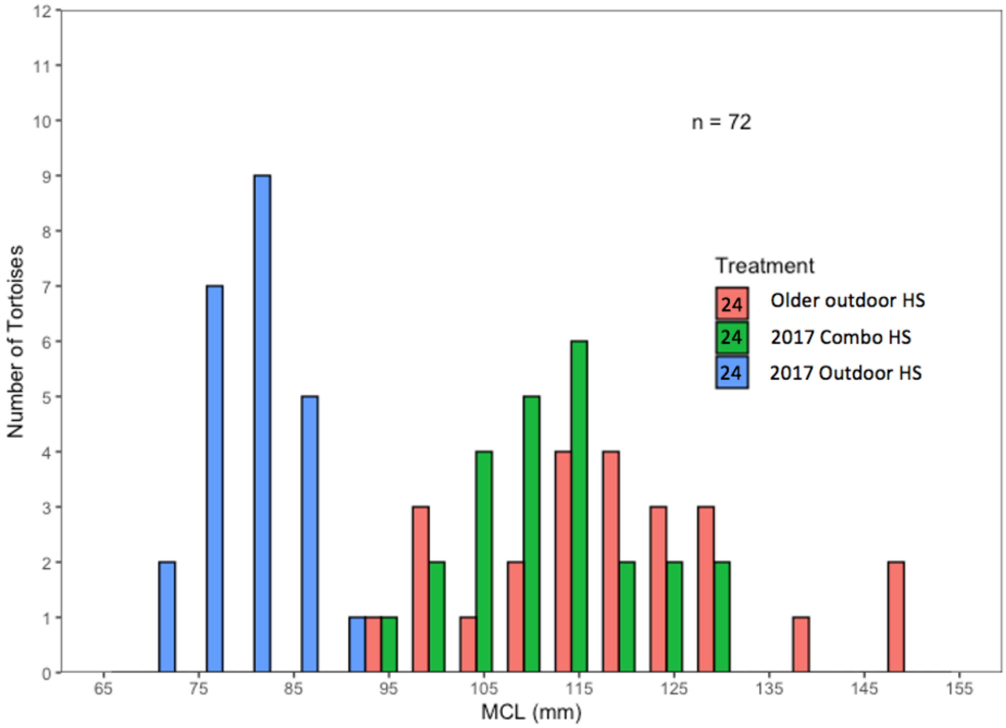
Figure 16: Size Distribution of Head-Started Tortoises Released in 2018



The size distribution in midline-carapace length (MCL mm) of head-started tortoises released in September 2018

Source: Collin J. Richter, University of California, Davis

Figure 17: Size Distribution of Head-Started Tortoises Released in 2019



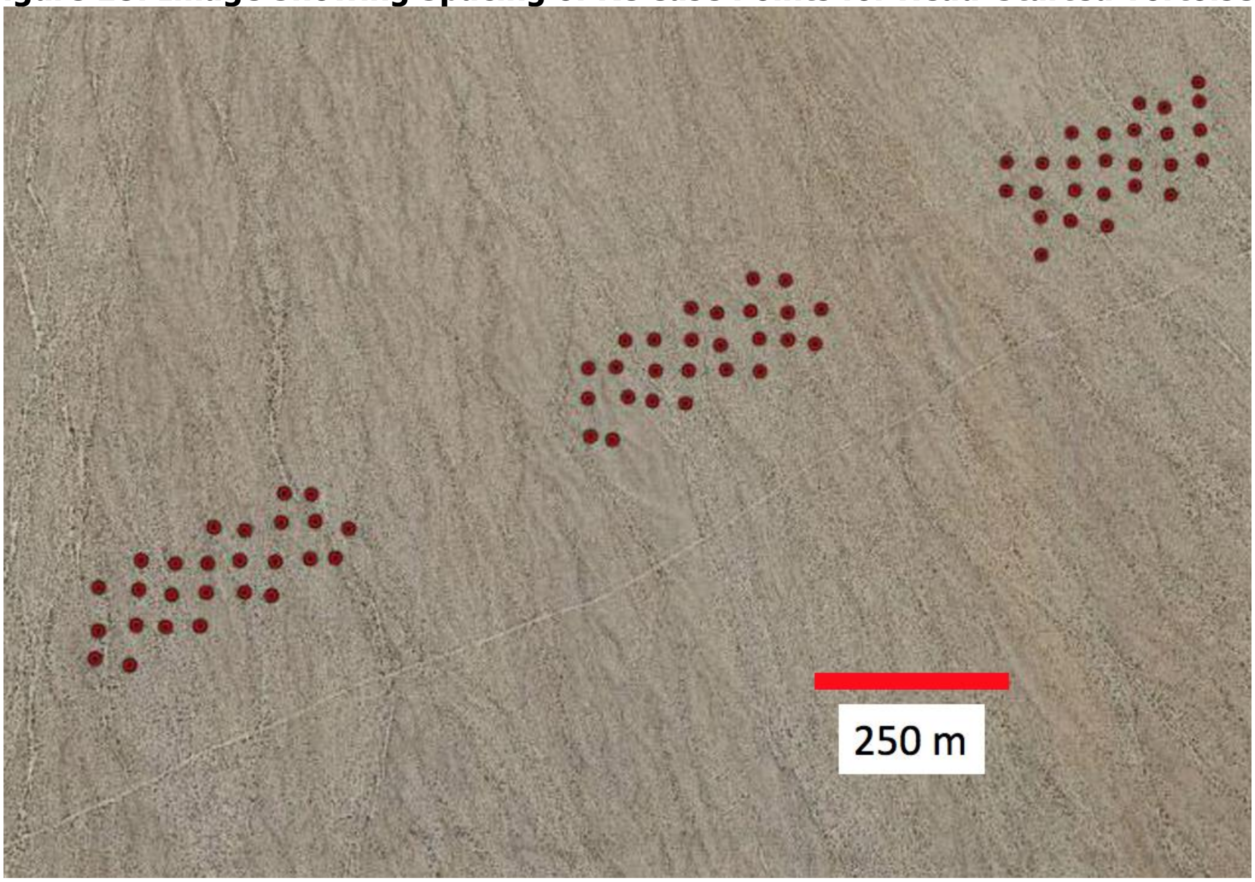
The size distribution in midline-carapace length (MCL mm) of head-started tortoises released in September 2019

Credit: Carmen M. Candal, University of Georgia

Release locations were chosen in the Mojave National Preserve where the mothers of the tortoises were originally found. Head-started tortoises were released at least 1.6 km from raised structures like power lines that could provide perching sites for ravens (Daly et al. 2019), at locations that allowed accessibility for frequent tracking, and that had suitable habitat for juvenile tortoises (Baxter 1988; Nafus et al. 2015a, Todd et al. 2016). At the study site, juvenile desert tortoises selected microhabitats with sandy soils, high-density perennial shrubs, abundant rodent burrows, and nearby washes (Todd et al. 2016). Washes have been shown to influence movement (Nafus et al. 2017a, Peaden et al. 2017) and provide increased forage (Jennings and Berry 2015).

Using ArcGIS (version 10.5; ESRI, Redlands, CA), a 0.6-km^2 rectangular release plot (300 x 2000 m) was identified parallel to a dirt, infrequently traveled access road. Release points were then generated in a grid every 50 m throughout the plot. Interior points were removed to create three equally spaced blocks 300 m apart that each contained 26 release points for a total of 78 release points (Figure 16). A buffer of 10 m around each release point was used to allow selecting a release refugium consisting of a large perennial shrub and an intact kangaroo rat (*Dipodomys* spp.) burrow (Nafus et al. 2015a, Todd et al. 2016, Daly et al. 2019). Before releasing each tortoise, the burrow was enlarged to provide a refuge large enough to conceal the released tortoise. Under this release protocol, the minimum possible distance between release burrows was 30 m. Final release points ranged between 150–350 m from the access road and between 1.9–2.5 km to the closest powerline. Release blocks were separated to allow tracking each block individually, facilitating the tracking of so many animals, and to minimize activity in each block. This process was used to establish separate rectangular release plots in both September 2018 and September 2019 (Figure 18).

Figure 18: Image Showing Spacing of Release Points for Head-Started Tortoises



Three large blocks where tortoises were released in September 2018 showing how release points were spaced 50 m apart. A similar, separate set of blocks was established a few km away for the releases in September 2019.

Image credit: Collin J. Richter, University of California, Davis

Radio transmitters from Advanced Telemetry Systems (ATS; Advanced Telemetry Systems, Maine) were attached to the fifth vertebral scute with gel epoxy (Devcon 5-minute epoxy gel, ITW Engineered Polymers, County Clare, Ireland) (Figure 19). Outdoor HS tortoises were outfitted with R1670 transmitters (3.1 g) and Combo HS were outfitted with the slightly larger R1680 model (3.6 g). Before the epoxy hardened, a thin coat of sand was applied to the epoxy to camouflage the transmitter package (Kazmaier et al. 2002). Each tortoise was checked 24 hours after release to make sure its transmitter was working. After the initial 24-hour check, tortoises were tracked within each release block twice per week for the first three weeks before reducing tracking frequency to once per week until winter hibernation. During the hibernation period (November–February), the juvenile tortoises were tracked every 10-14 days before returning to a weekly tracking schedule in March for the remainder of the study, concluding in September 2020. Tracking continued during the winter, though at a reduced rate, because juvenile desert tortoises may be active outside of burrows when weather is favorable (Figure 20), to determine if there were any winter mortalities away from burrows (Morafka 1994, Wilson et al. 1999). At each tracking occasion, a tortoise’s location was recorded to the nearest ±3 m using a handheld GPS (Garmin model GPSmap 76CSx, Olathe, Kansas).

Figure 19: Head-Started Tortoise Outfitted with Radio-Transmitter

A head-started tortoise is shown hiding in a burrow shortly after it was released into the wild. Radio-transmitters were affixed to the fifth vertebral scute of all released tortoises using gel epoxy, with the antenna trailing freely behind.

Photo credit: Kurt A. Buhlmann, Savannah River Ecology Laboratory

Figure 20: Head-Started Tortoise Resting Outside its Burrow

A head-started tortoise is seen resting outside its burrow one year after it was released.

Photo credit: Kurt A. Buhlmann, Savannah River Ecology Laboratory

Program R (R Core Team 2017) was used for statistical tests and significance assessed at alpha = 0.05. Survival probability as a function of size (midline carapace length) was analyzed by fitting a generalized linear model (GLM) using a binomial distribution (alive=1, dead=0) and logit link. Survival curves over time were calculated using a Kaplan-Meier estimator for each treatment group (R package 'survival'). Model-averaged predictions and 95 percent confidence intervals (CIs) of survival were generated across a range of MCL values (70-150 mm). Data are presented as group means ± 1 SE. Model residuals were visually inspected and Shapiro-Wilk tests were used to test model assumptions of normally distributed residuals.

Post-Release Survival Results

Annual Survival of Tortoises

The smallest head-started tortoises released in 2018 (those from the 2016 Outdoor HS release group) had the lowest annual survival of any of the release groups in any years in their first year after release at 68 percent (Figure 21; Table 3). In contrast, larger tortoises from both the Older Outdoor HS and 2016 Combo HS release groups had higher annual survival rates in their first year after release than the 2016 Outdoor HS group (Figure 21; Table 3). Annual survival of tortoises from all release groups in 2018 was higher the second year after release than in the first year (Table 3). Five tortoises released in 2018 had unknown fates after their first year due to radio-transmitter failures, but none were missing due to radio-transmitter failure in the second year. Annual survival of tortoises released in 2019 was similar among all three release groups (Figure 22; Table 3). Six tortoises released in 2019 had unknown fates after one year of radio-tracking due to radio-transmitter failures.

Table 3: Annual Survival of Released Tortoises

	Annual Survival Year 1	Annual Survival Year 2	Total Survival Over Two Years
2018 Release			
Older Outdoor HS	88.9%	95.8%	85.0%
2016 Combo HS	87.5%	100.0%	87.5%
2016 Outdoor HS	68.0%	100.0%	68.0%
All	82.2%	98.3%	80.8%
2019 Release			
Older Outdoor HS	87.0%		
2017 Combo HS	87.5%		
2017 Outdoor HS	89.5%		
All	87.9%		

Annual survival of all tortoises released in the three release groups in September 2018 and September 2019. Outdoor HS tortoises were raised entirely outdoors (6-7 years for Older Outdoor HS tortoises) and Combo HS tortoises were raised indoors their first year, then outdoors their second year. Survival calculations exclude any tortoises with unknown fates due to radio-transmitter failures.

Source: Summary statistics calculated by Brian D. Todd, University of California, Davis.

Figure 21: Survival of Tortoises Released in 2018

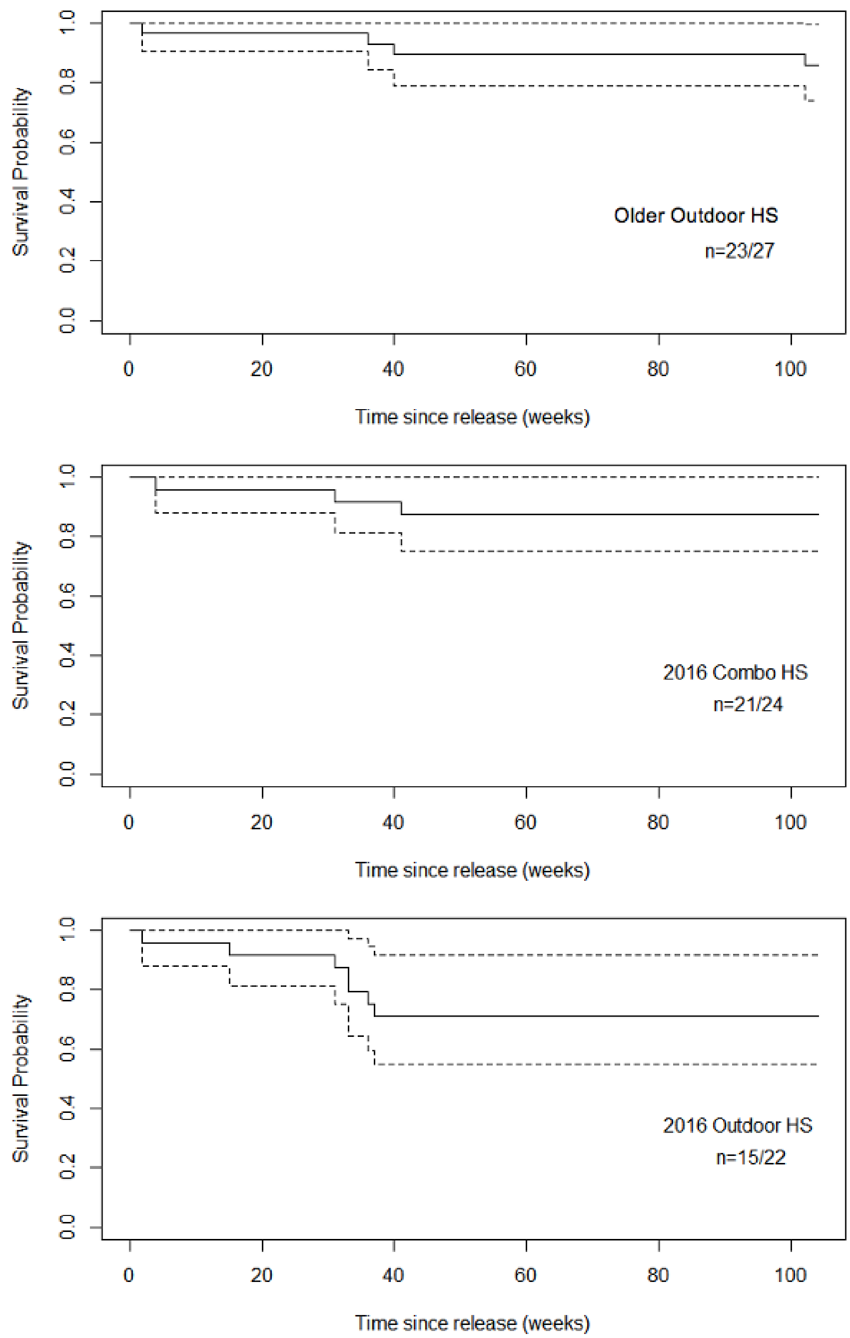
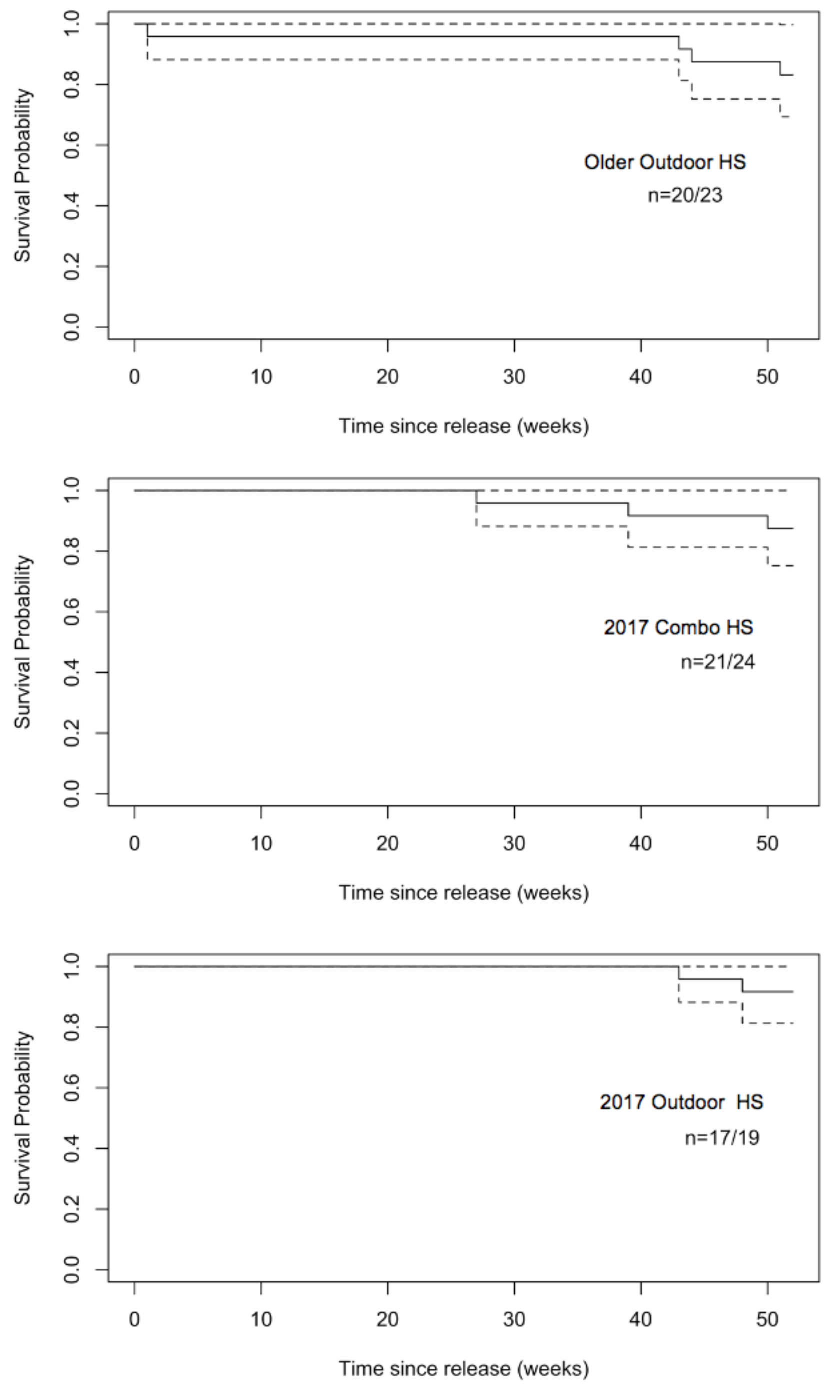


Figure 21 shows the two-year survival probability for each of the three groups of tortoises released in 2018. The dashed lines reflect uncertainty around estimated survival probabilities from lost individuals whose fates were unknown (and which therefore may have either survived or died). These losses may have been due to radio-transmitter failure or because the tortoises were killed where the transmitters and carcasses were not recovered. The numerator in each graph is the number of tortoises alive at the end of the study period and the denominator is the total number with known fates.

Source: Collin J. Richter, University of California, Davis

Figure 22: Survival of Tortoises Released in 2019



The first-year survival probability for each of the three groups of tortoises released in 2019 is shown in Figure 22. The dashed lines reflect uncertainty around the estimated survival probabilities due to lost individual tortoises whose fates were unknown, and which therefore may have either survived or died. These losses may have been due to radio-transmitter failure or because the tortoises were killed and the transmitters and carcasses not recovered. The numerator in each graph is the number of tortoises alive at the end of the study period and the denominator is the total number with known fates.

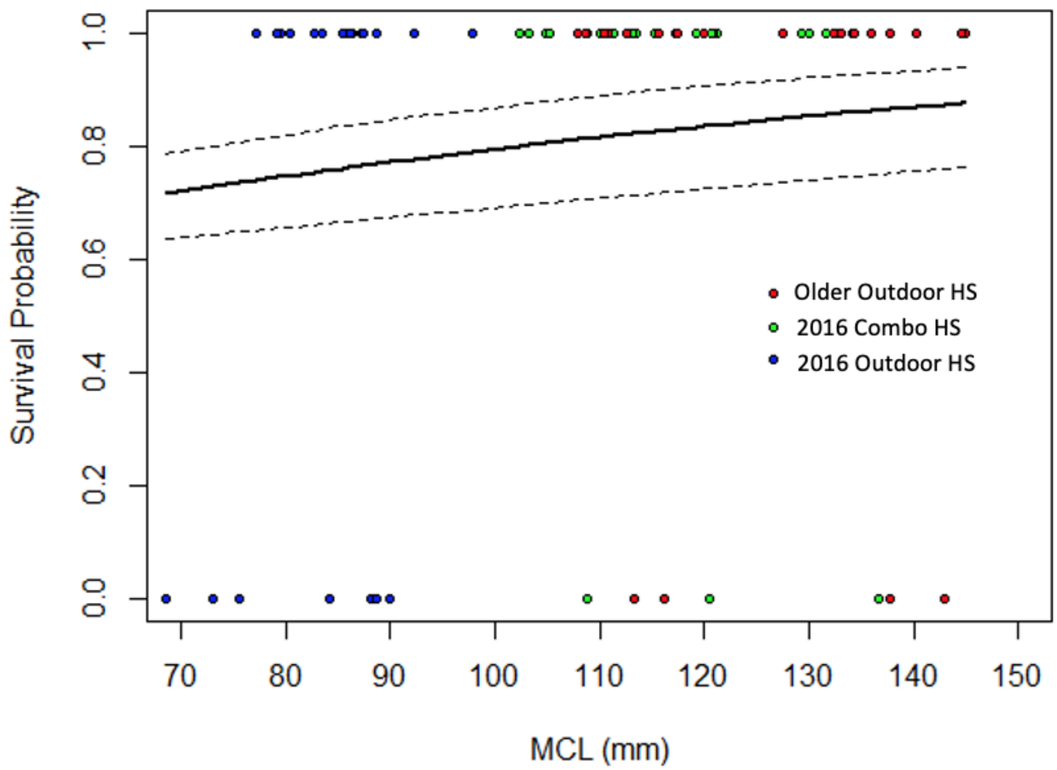
Credit: Carmen M. Candal, University of Georgia

Among the tortoises released in 2018 that were known to have died during the study, 10 were due to predation by mammals, two were due to predation by birds, and two were from unknown causes. Among the tortoises released in 2019 that had known fates and died over the study, eight were due to predation by mammals and one was due to predation by a bird.

Effect of Size at Release on Survival

Survival of head-started tortoises increased significantly with size at release for tortoises released in 2018 (P<0.001; Figure 23)—for which there were two years of radio-tracking data—and for tortoises released in 2019 (P<0.001; Figure 24)—for which there was one year of radio-tracking data.

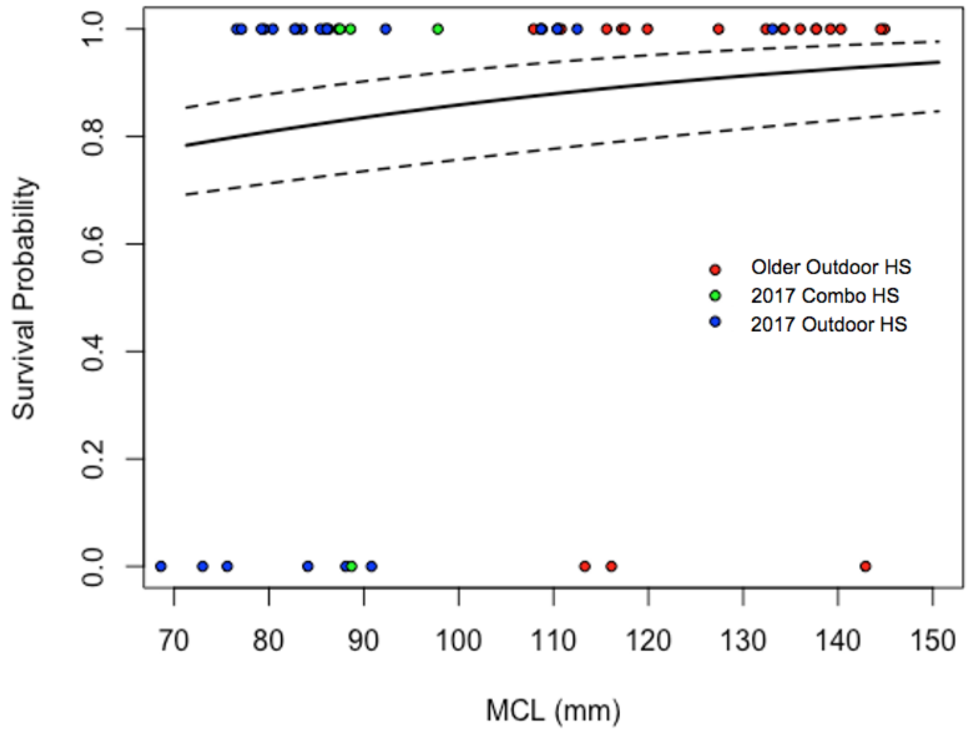
Figure 23: Survival as Function of Size for Tortoises Released in 2018



The probability of a tortoise released in 2018 surviving over the two years of study increased with size (midline carapace length, MCL). Animals with unknown fates were not included in this analysis and are not shown in Figure 23.

Source: Collin J. Richter, University of California, Davis

Figure 24: Survival as Function of Size for Tortoises Released in 2019



The probability of a tortoise released in 2019 surviving over one year of study increased with size (midline carapace length, MCL). Animals with unknown fates were not included in this analysis and are not shown in Figure 24.

Source: Carmen M. Candal, University of Georgia

Post-Release Survival Discussion

There are very few estimates of survival of recently hatched or other small, juvenile Mojave desert tortoises free-ranging in the wild. From what has been published to date, the estimates of post-release survival of head-started tortoises studied here were uniformly higher than would have been expected without head-starting intervention. For instance, annual survival rates of recently hatched tortoises over their first few years of life in the same area as the present study were estimated at 48±9 percent (Tuberville et al. 2019). In other parts of the Mojave Desert, overall annual survival was estimated at 68 percent for the first year after release for juvenile tortoises aged 0.5-4 years that received some prior captive husbandry (Nafus et al. 2017a). In contrast, the lowest annual survival estimate in the present study was 68 percent, and that was for two-year-old 2016 Outdoor HS tortoises that were the smallest of the three groups released in 2018. Notably, all Outdoor HS tortoises released at two years of age were below the 100 mm MCL threshold size recommended for release (Nagy et al. 2015b). The next lowest annual survival estimate in the present study was 87 percent for Older Outdoor HS tortoises released in 2019. For the most part, therefore, head-starting tortoises, regardless of the duration or husbandry method, resulted in notable improvements in survival of the tortoises once released, the ultimate goal of all head-starting programs.

The combined rearing of tortoises indoors their first year, followed by a second year outdoors, produced tortoises that survived at rates comparable to tortoises 4-5 years older that were reared exclusively outdoors. This is encouraging and suggests that just two years of head-starting with the Combo method can feasibly substitute for 6-7 years of investment in exclusive outdoor rearing. In contrast, tortoises reared outdoors for just two years before release sometimes survived at lower rates than both other groups. This is unsurprising given that tortoises reared outdoors for just two years had average sizes at release that were below the 100 mm MCL size threshold recommended (Nagy et al. 2015b). Nevertheless, their fates were useful in further proving the value of increased size for increased survival.

Regardless of the head-started release group, survival rates increased with tortoise size at release into the wild. This correlation likely explains why the Combo HS tortoises just 2 years old survived at similar rates to 6–7-year-old, Older Outdoor HS tortoises, despite their age differences. Both Combo HS and Older Outdoor HS tortoises were of similar size, generally larger than the 100 mm MCL size threshold at which survival is known to increase appreciably (Nagy at el. 2015b). Rather than an explicit threshold of 100 mm MCL, however, these results show that tortoise survival rates increase proportionally with larger size.

CHAPTER 5: Post-Release Movements of Head-Started Tortoises

Assessing Post-Release Movements of Head-Started Tortoises

As described in Chapter 4, tortoises from three groups were released in September 2018 and again in September 2019: older Outdoor HS tortoises, Combo HS tortoises, and Outdoor HS tortoises. These tortoises were radio tracked weekly until they died, were lost from transmitter failures, or to the end of the study. Several movement metrics were calculated for each tortoise using their locations from each radio-tracking event. Mean step length was calculated as the mean distance between two successive radio-tracking events. Radio-tracking events over winter hibernation, when tortoises do not move, were excluded from the calculation. The distance traveled to first winter hibernation location was calculated as the total path length along all recorded points between the time of release and the winter hibernation burrow where a tortoise settled its first winter; tortoises that did not survive the entire period were removed from the calculation. Distance traveled in the first year was calculated as the total path length along all recorded points between time of release and the end of the first year of tracking. Any tortoises that did not survive the entire period were removed from the calculation.

For tortoises released in 2018, the distance traveled in the second year was calculated as the total path length along all recorded points between the location at the end of the first year and the end of the second year of tracking. Any tortoises that did not survive the entire period were removed from the calculation. Similarly, for tortoises released in 2018, the total distance traveled over both years was calculated as the total path length along all recorded points between the location at release and the end of the second year. Any tortoises that did not survive the entire period were removed from the calculation. Displacement distances (the simple straight-line distance between two points) were calculated from release location to first winter hibernation, release location to end of the first year, and, for tortoises released in 2018, from start of to the end of the second year, and from release location to the end of second year for all tortoises that survived the entire periods.

Linear mixed-effects models (LME; 'nlme' package, 'lme' function) were used to compare all movement metrics among the three release groups, separately for tortoises released in 2018 and 2019. Maternal ID was included as a random effect in all models to account for possible maternal effects. Tukey tests were used for post-hoc pair-wise comparisons.

Post-Release Movement Results

In both release years, the Older Outdoor HS tortoises typically had the greatest movements of all three release groups, and the younger Outdoor HS tortoises often had the smallest movements. This was generally true for mean-step lengths between successive tracking events and for total distances traveled for all time points, although there was variation in the significance of these lengths among the three release groups, as shown in Table 4. Among tortoises released in 2018, the mean step lengths and total distances traveled for all time points were similar between the Older Outdoor HS tortoises and the similarly sized 2016 Combo HS tortoises; but in the 2019 release, only the Older Outdoor HS tortoises tended to have greater mean step lengths or distances traveled to all time points, relative to the 2017 Combo HS and 2017 Outdoor HS tortoises.

Table 4: Mean Step Lengths and Distances Traveled for Released Tortoises

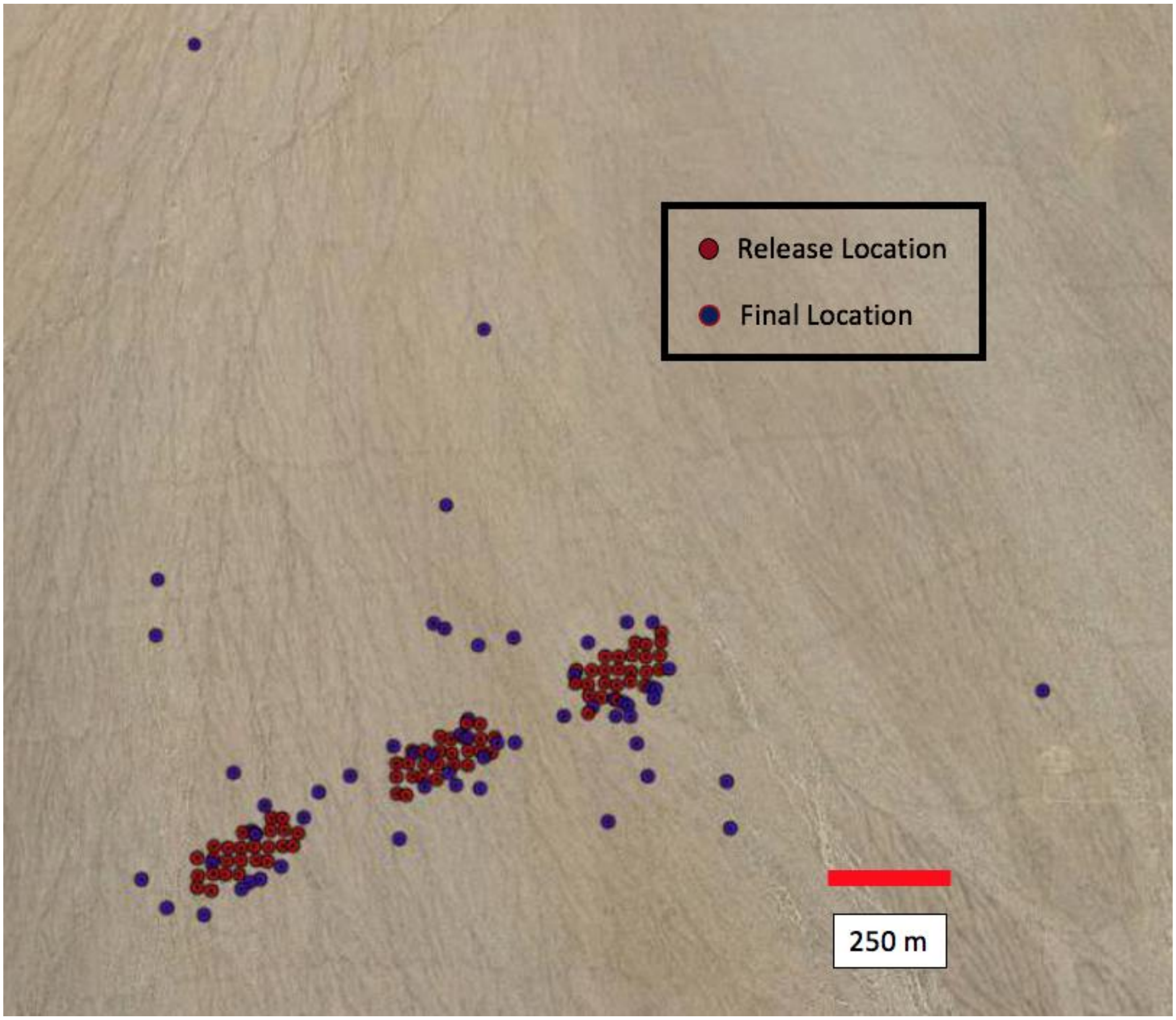
	Mean Step Length (m)	Distance Traveled to First Winter (m)	Distance Traveled in First Year (m)	Distance Traveled in Second Year (m)	Total Distance Traveled Over Both Years (m)
2018 Release					
Older Outdoor HS	51.8 (±8.0)[a]	481.0 (±141.4)	1395.3 (±219.5)	1309.8 (±223.1)[a]	2414.8 (±349.9)
2016 Combo HS	34.1 (±3.3)[ab]	238.4 (±55.4)	1000.3 (±109.6)	1127.7 (±218.4)[ab]	1966.3 (±275.7)
2016 Outdoor HS	27.6 (±3.1)[b]	376.2 (±61.3)	1052.3 (±153.3)	525.4 (±72.3)[b]	1473.0 (±197.4)
P-value	**0.01**	0.27	0.22	**0.05**	0.12
2019 Release					
Older Outdoor HS	46.8 (±16.2)[a]	646.4 (±107.4)[a]	1165.4 (±129.8)[a]		
2017 Combo HS	18.2 (±1.4)[b]	316.1 (±45.9)[b]	676.0 (±55.0)[b]		
2017 Outdoor HS	14.5 (±1.9)[b]	240.3 (±66.7)[b]	535.8 (±69.9)[b]		
P-value	**<0.001**	**0.001**	**<0.001**		

Comparison of movement metrics for tortoises from each of three release groups in 2018 and 2019. Mean step length is the mean distance between two consecutive radio-tracking events for each tortoise. Distance traveled is the total path length of all movements along the radio-tracked path that the tortoise took for each described time period. Outdoor HS tortoises were raised entirely outdoors (6-7 years for Older Outdoor HS tortoises) and Combo HS tortoises were raised indoors their first year then outdoors their second year. Values shown are means ± 1 SE. Superscript letters denote pair-wise comparisons from post-hoc tests and differentiate groups that differ significantly at the alpha = 0.05 level.

Source: Summary statistics and calculations provided by Collin J. Richter (University of California, Davis) and Carmen M. Candal (University of Georgia).

Although they were released in an orderly grid, the head-started tortoises were free to disperse and use the habitat as needed. Some tortoises moved farther from their release site than others and some ended up closer together than they were at release. Tortoises made use of multiple burrows over time, just as they would in the wild. The release and final resting locations of all tortoises are shown for the 2018 release in Figure 25 and for the 2019 release in Figure 26.

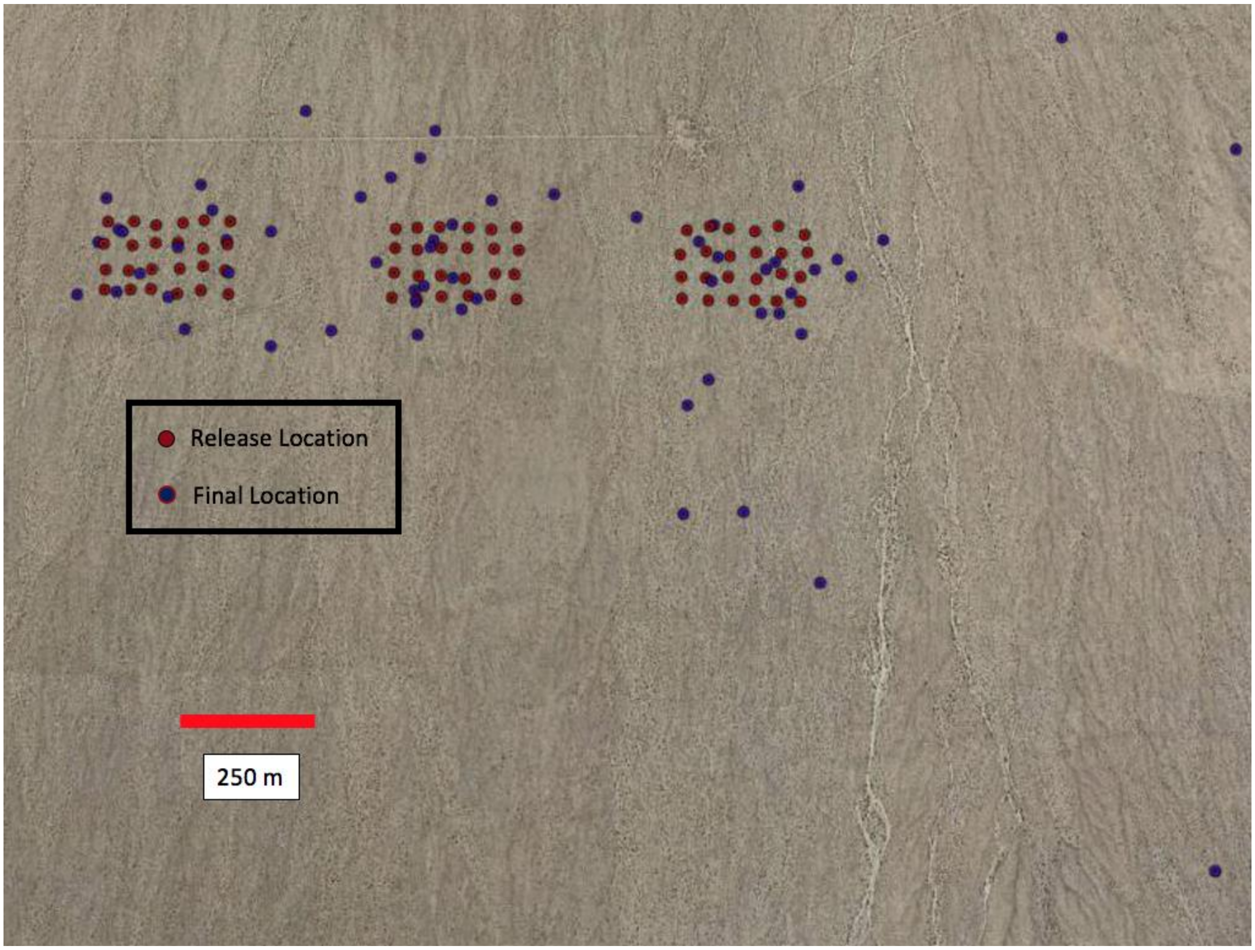
Figure 25: Release and Final Locations of Tortoises Released in 2018



The release locations (shown in red) and final locations (shown in blue) of all head-started tortoises released in September 2018 and radio-tracked until the study conclusion in September 2020. The red bar shows the scale for comparison.

Image credit: Collin J. Richter, University of California, Davis

Figure 26: Release and Final Locations of Tortoises Released in 2019



Release locations (shown in red) and final locations (shown in blue) of all head-started tortoises released in September 2019 and radio tracked until the study's conclusion in September 2020. The red bar shows the scale for comparison.

Image credit: Collin J. Richter, University of California, Davis

The Older Outdoor HS tortoises generally had the greatest net displacement distance, a measure of how far a tortoise was located relative to its release location or location at the start of a tracking year. As shown in Table 5, the Combo HS tortoises generally settled closest to their release sites compared with the other two release groups in both release years. The smallest tortoises of the three release groups—the younger Outdoor HS tortoises—were often located away from their starting points at distances intermediate to those of the Older Outdoor HS and Combo HS release groups in both release years.

Table 5: Displacement Distances Relative to Release or Starting Locations

	Displacement to First Winter (m)	Displacement to End of First Year (m)	Displacement to End of Second Year (m)	Total Displacement Over Both Years (m)
2018 Release				
Older Outdoor HS	349.0 (±128.5)	404.3 (±149.8)	186.7 (±75.1)[a]	588.1 (±157.9)[a]
2016 Combo HS	114.1 (±51.6)	94.1 (±19.7)	47.2 (±6.4)[ab]	105.6 (±18.1)[b]
2016 Outdoor HS	255.4 (±50.9)	327.3 (±64.3)	16.3 (±3.9)[b]	337.3 (±68.6)[ab]
P-value	0.25	0.07	**0.05**	**<0.01**
2019 Release				
Older Outdoor HS	400.4 (±107.3)[a]	423.1 (±104.8)[a]		
2017 Combo HS	98.7 (±23.1)[b]	118.3 (±24.5)[b]		
2017 Outdoor HS	162.5 (±66.2)[ab]	102.7 (±16.2)[b]		
P-value	**0.03**	**0.002**		

Comparison of displacement distances for tortoises in each of three release groups in 2018 and 2019. Displacement distance is the straight-line distance between the release location and final location at the end of the period except for "Displacement to End of Second Year," which is the straight-line distance between a tortoise's location at the beginning and end of the second year of tracking. Outdoor HS tortoises were raised entirely outdoors (6-7 years for Older Outdoor HS tortoises) and Combo HS were raised indoors their first year then outdoors their second year. Values shown are means (± 1 Standard Error). Superscript letters denote pair-wise comparisons from post-hoc tests and differentiate groups that differ significantly at the alpha = 0.05 level.

Source: Summary statistics and calculations provided by Collin J. Richter (University of California, Davis) and Carmen M. Candal (University of Georgia).

Post-Release Movement Discussion

For head-starting to be an effective conservation strategy, the tortoises released after captivity must both survive at high rates and remain near release sites. Animals that remain near release sites are more likely to be recruited into target populations in need of recovery. Dispersal outside target populations could increase the risk of death in transit, or otherwise remove them from the population of interest. Thus, a primary goal of this study was to determine the extent to which this more hands-on approach of indoor rearing would affect the movement behaviors of head-started desert tortoises when compared with the behaviors of tortoises reared outdoors with longer exposure to their natural habitat.

The results of the present study are encouraging; Combo HS tortoises often had the highest levels of site fidelity after release. Despite their comparable size to older head-started tortoises, Combo HS tortoises generally moved half as far and settled half the distance from their release locations as did Older Outdoor HS tortoises. Combo HS tortoises instead typically had movements and displacement distances similar to their same-aged but smaller siblings reared entirely outdoors (both 2016 and 2017 Outdoor HS tortoises).

CHAPTER 6: Knowledge Transfer Activities

Knowledge Gained

This research study found that one year of rearing tortoises indoors after hatching produces high-growth rates that later increase their survival rates when released to the wild. Although both exclusive outdoor rearing and combination rearing with a first year indoors can result in high survival rates after release into the wild, the greatest benefit of head-starting appears to be driven by the size of the tortoises at release. Smaller tortoises reared exclusively outdoors for just two years did not always have the same higher rates of survival seen in larger tortoises regardless of the age of the larger tortoises. Also, when released, tortoises reared using the Combo method generally showed signs of remaining close to their initial release locations, an encouraging sign that head-starting tortoises in this fashion may appreciably contribute to the recovery of target populations.

Target Audiences

Several agencies and stakeholders are likely to benefit from the knowledge gained in this study, including, but not limited to:

- Public wildlife agencies like the U.S. Fish and Wildlife Service and the California Department of Fish and Wildlife that make management decisions that affect wildlife and who are tasked with protecting and recovering the Mojave desert tortoise.
- Private industry partners, whose solar-energy development plans benefit from clear mitigation strategies that reduce harm to, or help recover, Mojave desert tortoise populations.
- Public land management agencies like the U.S. Bureau of Land Management, the U.S. National Park Service, and others whose managed lands include populations of Mojave desert tortoises in need of protection or recovery actions.
- Members of the public interested in the preservation of our shared natural heritage and wildlife and their management for the public good.
- Scientists with research goals to increase the feasibility and use of effective tools to recover declining Mojave desert tortoise populations. The methods and case study of this project may also inform scientists considering head-starting other imperiled species.

Transfer Activities

Primary transfer activities focused on the timely delivery of high-quality science to decision-makers, the public, and the scientific community. This was accomplished in several ways, including meetings with the California Energy Commission, annual presentations at the Annual Symposium of the Desert Tortoise Council (whose attendees include the diverse stakeholders listed earlier under "target audiences"), annual reports to the state and national wildlife permitting agencies, publications in peer-reviewed scientific journals, and direct conversations by phone, in person, or through emails with scientists and managers in public agencies. The U.S. Fish and Wildlife Service is currently developing a "Population Augmentation Strategy for the Mojave Desert Tortoise Recovery Program" and incorporating head-starting methods, information, and knowledge from this report.

Work published in peer-reviewed scientific journals that have helped share the research, recommendations, and conclusions from this study include:

- McGovern PA, Buhlmann KA, Todd BD, Moore CT, Peaden JM, Hepinstall-Cymerman J, Daly JA, Tuberville TD. 2021. The effect of size on post-release survival of head-started Mojave Desert Tortoises. *Journal of Fish and Wildlife Management*, In Press.
- McGovern PA, Buhlmann KA, Todd BD, Moore CT, Peaden JM, Hepinstall-Cymerman J, Daly JA, Tuberville TD. 2020. Comparing husbandry techniques for optimal head-starting of the Mojave desert tortoise (*Gopherus agassizii*). *Herpetological Conservation and Biology* 15(3):626–641.

Additional publications reporting the survival and movement results from the entire two years of post-release radio tracking reported here are expected to be forthcoming for publication in peer-reviewed management or wildlife scientific journals.

Presentations of the results at annual meetings of the Desert Tortoise Council include:

- Todd BD, McGovern PA, Peaden JM, Daly JA, Buhlmann KA, Tuberville TD. February 22, 2020. Evaluating techniques for optimal head-starting of the Mojave Desert Tortoise (*Gopherus agassizii*). At the 45th Annual Meeting and Symposium of the Desert Tortoise Council, Las Vegas, Nevada.
- McGovern PA, Buhlmann KA, Todd BD, Moore CT, Peaden JM, Hepinstall-Cymerman J, Tuberville TD. February 23, 2019. Post-release survival until dormancy of combo-reared head-started Mojave Desert Tortoises (*Gopherus agassizii*). At the 44th Annual Meeting and Symposium of the Desert Tortoise Council, Tucson, Arizona.
- Peaden JM, Tuberville TD, Buhlmann KA, Todd BD. February 25, 2018. Update on Desert Tortoise Head-starting Studies at the Mojave National Preserve, 43rd Annual Meeting and Symposium of the Desert Tortoise Council, Las Vegas, Nevada.

Additional presentations to the broader scientific community include:

- McGovern PA, Buhlmann KA, Todd BD, Moore CT, Peaden JM, Tuberville TD. August 7, 2019. Post-release movement and survival of differentially head-started Mojave desert tortoises (*Gopherus agassizii*): preliminary results. Turtle Survival Alliance, Tucson, Arizona.
- McGovern PA, Buhlmann KA, Todd BD, Moore CT, Peaden JM, Tuberville TD. July 27–29, 2019. Post-release movement and survival of differentially head-started Mojave desert tortoises (*Gopherus agassizii*): preliminary results. Southwest Partners in Amphibian and Reptile Conservation, Rodeo, New Mexico.
- McGovern PA, Hepinstall-Cymerman J, Moore C, Todd BD, Tuberville TD, Buhlmann KA. February 23, 2018. Changing the survival formula of the Mojave Desert Tortoise *(Gopherus agassizii*) through head-starting. Southeastern Partners in Amphibian and Reptile Conservation Annual Meeting, Helen, Georgia.
- Tuberville TD, Buhlmann KA, Quinn DP, Daly JA, Todd BD, Peaden JM, Nafus MG. Developing head-starting strategies that work for Gopher Tortoises and Desert

Tortoises: an iterative process. August 7, 2017. 15th Annual Symposium on the Conservation and Biology of Tortoises and Freshwater Turtles, Turtle Survival Alliance, Charleston, South Carolina.

The research in this study was featured in an article in the *Washington Post* that included a short documentary video posted to YouTube.

Washington Post article:

- https://www.washingtonpost.com/brand-studio/wp/2018/09/09/feature/can-solar-energy-and-wildlife-coexist/

YouTube video:

- https://www.youtube.com/watch?v=4TINHeMuwg8

Meetings with the technical advisory committee (TAC) were held on October 11, 2017, October 2, 2018, and October 24, 2019. The TAC was composed of diverse stakeholders including representatives from the U.S. Fish and Wildlife Service, California Department of Fish and Wildlife, U.S. Bureau of Land Management, Edwards Air Force Base, NRG Energy, California Energy Commission, and Turtle Survival Alliance.

A field trip and site visit for stakeholders and attendees of the Desert Tortoise Council 2020 Annual Symposium to the research site where the research and results were described took place on February 20, 2020.

CHAPTER 7: Conclusions and Recommendations

Summary of Major Findings

This research project concludes that the addition of indoor rearing the first year after hatching can substantially improve both the feasibility and effectiveness of head-starting Mojave desert tortoises. Survival in captivity was 100 percent indoors, and nearly as high for tortoises reared outdoors, both in the first year (91 percent), and in later years (96-98 percent). Tortoises reared indoors grew nearly 300 percent more than those reared exclusively outdoors. As a result, after two years of total head-starting, tortoises reared indoors their first year were similar in size to those that had been reared exclusively outdoors for 6-7 years. They likewise had shells that were as hard as those of tortoises that had been reared exclusively outdoors for 6-7 years. Whether reared indoors their first year or exclusively outdoors, and regardless of whether they had been head-started for two years or seven, all tortoises head-started on the project were of healthy body condition at the time of release.

Survival after release was high for head-started tortoises, a primary goal of any population augmentation project. Because size at release appeared to be the greatest determinant of head-started tortoise survival in the wild, the addition of indoor rearing was critical. Tortoises reared for just two years survived in the wild after release at levels similar to those 6–7 years due to their similar sizes (87–89.5 percent annually), a feat achieved with just one year of indoor rearing after hatching. Moreover, the use of indoor rearing did not appear to have any negative effects on movement behaviors after release. Instead, movement rates appeared to be driven more by tortoise age than by size or prior husbandry. All head-started tortoises settled within approximately 500 m of their release sites, and younger tortoises typically settled closer than older tortoises, often within approximately 150 m.

Applications and Recommendations

This project demonstrates the effectiveness of indoor rearing to accelerate the growth rates of Mojave desert tortoises in head-starting programs. The following recommendations are based on the research findings of this project:

- Rearing hatchling desert tortoises indoors during their first year can dramatically increase growth rates by keeping tortoises feeding and growing over their first winter, when tortoises outdoors would normally be inactive. The enhanced growth from indoor rearing produces juveniles in just one year that exceed the previously recommended threshold size for release. Incorporating an indoor-rearing phase into head-starting programs therefore reduces the time required in captivity to rear tortoises to a release size, increasing the number of offspring that can be produced by head-starting programs.
- Indoor rearing should include the following measures to ensure the health and growth of captive desert tortoises.
    - Use of adequate lamps to provide warm basking sites for tortoises.
    - Use of UVB lights for tortoises to metabolize calcium and vitamin D3.

  - Frequent use of calcium and vitamin D3 powder supplements at each feeding.
  - Use of moist hide boxes to ensure healthy shell growth and minimize shell pyramiding.
  - Use of a varied diet that mimics a natural diet. The diet of tortoises in this study included Mazuri Tortoise Diet 5M21 and at least three of the following greens at each feeding: dandelion, mustard greens, turnip greens, collards, endive, and escarole.
  - Weekly or twice weekly soaking to promote hydration and good shell growth.
  - Spot-cleaning rearing tubs one day after each feeding.
  - Replacement of substrate and enclosure cleaning at least monthly.
  - Use of protocols that minimize cross-contamination and potential introduction of disease.
  - Minimal additional interaction with the tortoises aside from the maintenance actions just listed.
- Head-starting desert tortoises with a combination of indoor and outdoor rearing produces robust juveniles that exhibit high post-release survivorship and high site fidelity without apparent negative effects on shell hardness, body condition, or post-release movement behaviors. The outdoor-rearing phase may provide a source of enrichment by providing head-started tortoises opportunities to dig burrows and experience environmental cues they will encounter in the wild after release. Future research should further investigate the extent to which combined indoor and outdoor rearing methods improves survival rates compared with rearing tortoises solely indoors for a single year before releasing them (i.e., without a second year of captivity in protected outdoor enclosures).
- Survival increases with size at release, regardless of head-starting durations. Although no raven predation was observed on tortoises larger than 90 mm mid-line carapace length, survival will vary depending on habitat quality, abundance of predators (for example, ravens and coyotes), climate, and other factors. Site-specific conditions and program-specific objectives are factors for consideration when determining the ideal size for release and the most efficient, logistically feasible methods for rearing tortoises to that size.
- Supplemental feeding during the outdoor-rearing phase significantly increases annual growth rates, reducing captivity duration (though not as much as indoor rearing). Supplemental feeding becomes increasingly important over the lifetime of head-starting programs as natural forage in pens is depleted.
- Study outcomes corroborate previously established recommendations to conduct releases in the fall after ravens have completed nesting, and to release head-started tortoises equal to or greater than 1.6 km away from perching structures. These measures, in combination with larger release sizes, together contribute to the high post-release survival rates of head-started desert tortoises.

CHAPTER 8: Benefits to Ratepayers

Investments to increasingly develop California's deserts are driven largely by growing energy demands and mandates for greater electricity production from solar and other renewable energy sources. The development of utility-scale solar energy facilities impacts both environmentally sensitive areas and protected species, including the Mojave desert tortoise. The legally protected status of these species requires sometimes costly and time-intensive biological and environmental reviews that can require mitigation measures to minimize or offset harm to species that will be affected by proposed construction. Any measures that can effectively and efficiently reduce harm or mitigate new impacts may therefore help expedite biological reviews and broaden the portfolio of options available for decision-makers, reducing financial burdens and ultimately lowering costs for California utility ratepayers. This study's findings furthermore provide a scientific foundation upon which wildlife agencies can confidently prescribe mitigation methods.

By focusing on a science-based evaluation of prescribed recovery actions for a listed species, this project helps minimize conflicts between promoting conservation of special-status species while supporting the environmentally sustainable deployment of renewable-energy facilities in California's deserts. Ultimately, the results of this study can help agencies make better decisions that balance the preservation of California's unique natural heritage with the energy needs of its residents, subsequently lowering utility costs in the process.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
Augmentation	The addition of individuals of a species into a population to increase the size of the population.
CDFW	California Department of Fish and Wildlife.
CI	Confidence interval
cm, cm^3	Centimeter, cubic centimeter
Combo HS	Head-started tortoises reared using a combination of two methods that included rearing them indoors for their first year after hatching and then outdoors in predator-proof enclosures for their second year before release.
GLM	Generalized linear model
IDTRF	Ivanpah Desert Tortoise Research Facility
km	Kilometer
LME	Linear mixed effects
M, m^2	Meter, Square meters
MCL	Midline Carapace Length, a common measure of the length of a tortoise.
mm	Millimeter
Older Outdoor HS	Head-started tortoises that were reared exclusively outdoors in predator-proof enclosures and that were at least four years old.
Outdoor HS	Head-started tortoises that were reared exclusively outdoors in predator-proof enclosures.
SE	Standard error
SHI	Shell hardness index
TAC	Technical Advisory Committee
U.S.	United States
USFWS	United State Fish and Wildlife Service.
VHF	Very High Frequency

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