

Review

Conservation through Collaboration: Regional Conservation Programs of the North Carolina Zoo

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Abstract: In response to rapid biodiversity losses in recent decades, zoos have become more engaged in conservation issues. Solutions to conservation challenges are complex and require collaborative efforts across organizations. Zoos can be effective partners that can contribute diverse expertise and resources to protect wildlife and their habitats. While zoos often partner with international organizations to facilitate field-based conservation projects on the exotic animals they exhibit, some of the most meaningful conservation and education initiatives are conducted locally in partnership with local organizations. A core part of the mission of the North Carolina Zoo (Asheboro, NC, USA) is the conservation of wildlife and their natural habitats, both regionally and internationally. The goal of this article is to review the North Carolina Zoo's regional conservation programs and the importance of partnerships with other local organizations in accomplishing shared goals. North Carolina Zoo plays an important role in regional conservation by protecting and managing natural lands, protecting declining amphibians through headstarting and habitat management, rehabilitating native wildlife, and working on local outreach and sustainability projects to reduce impacts on natural resources and inspire others to get involved in conservation. These programs were developed through partnerships with local and state government agencies, academic institutions, non-profit organizations, other zoos and aquariums, schools, libraries, and businesses. These collaborations have been instrumental in developing and implementing successful projects by pooling limited resources and sharing crucial expertise. They demonstrate how zoos are evolving to become leaders and partners in conservation, research, and education to protect local species and natural resources.



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1. Introduction

Global biodiversity is under severe threat from human impacts, including habitat loss, pollution, overexploitation, emerging diseases, invasive species, and climate change. In the past 500 years, humans have triggered a wave of extinction and decline that may be comparable in both rate and magnitude to the five previous mass extinctions in Earth's history [1,2]. The rate of this sixth mass extinction has been estimated as 1000 times the background rate of extinction [3], and over one-third of all known vertebrates are decreasing in population size and geographic range [4]. These losses will have negative cascading consequences on ecosystem functioning and ecological services.

Slowing down biodiversity loss is one of the greatest challenges facing humans today. While many groups are working to address threats to biodiversity, such as government agencies, academic institutions, non-profit organizations, and private landowners, collaboration between organizations is often important for achieving shared goals. Collaborative conservation includes efforts to preserve, protect, and/or sustainably manage natural resources by two or more partners working together, often to set goals, make decisions, and implement actions [5]. Collaborative efforts are increasingly recognized as important for

addressing landscape-scale issues, and they are valuable for sharing resources, expertise, and diverse perspectives that drive innovation [6].

During the last 50 years, zoos have evolved from serving as entertainment venues to becoming centers for conservation, research, and education [7–9]. A key driver of this change was the development of captive-breeding programs first implemented to sustainably manage populations housed in zoos [9], and later applied to captive-breeding and release programs for threatened species. Thus, in response to growing biodiversity losses, zoos have become more engaged in conservation issues. Annually, zoos and aquariums accredited by the Association of Zoos and Aquariums (AZA) spend over USD 217 million on field conservation with more than 960 partners [10], and host over 183 million visitors [11]. This demonstrates the opportunities for these institutions to play an important role in environmental education and conservation of wildlife and their natural habitats. Zoos have become valuable partners in the recovery of threatened species by contributing to the care, research, and genetic management of zoo-managed populations, facilitating captive-breeding and reintroduction programs, and funding and participating in field-based conservation efforts [7,8,12]. Thus, conservation activities can occur *in situ*, *ex situ*, or both, and innovative solutions that bridge or blur these concepts are becoming increasingly important in species conservation [13]. While zoos often partner with international organizations to fund and assist with field-based conservation and research projects on the exotic animals they exhibit, some of the most meaningful conservation and education initiatives are conducted locally in partnership with local organizations.

A core part of the mission of the North Carolina Zoo (NCZ) is to conserve wildlife and their natural habitats. The scope of NCZ's conservation activities is geographically and taxonomically broad. Internationally, some of the current projects focus on protecting vultures and gorillas in Africa, translocating rare birds on Pacific islands, and developing software that empowers rangers worldwide in the fight against the illegal wildlife trade. Closer to home, NCZ plays an important role in regional conservation by protecting and managing natural lands, protecting threatened amphibians through headstarting and habitat management, rehabilitating native wildlife, and working on local outreach and sustainability projects to reduce NCZ's impact on natural resources and inspire guests and community members to get involved in conservation. These regional conservation programs were developed through partnerships with local and state agencies and other organizations. These collaborations have been instrumental in developing and implementing successful projects by pooling limited resources and sharing crucial expertise.

The purpose of this article is to review NCZ's regional conservation programs and the importance of partnerships with other local conservation organizations in accomplishing shared goals that could not be achieved by working alone. Although NCZ has made many other significant contributions to conservation and research, including international and zoo-based initiatives, we focus this article on conservation of native species and natural resources in North Carolina. We also use our experiences to provide recommendations for other zoos to begin or become involved with local conservation initiatives.

2. North Carolina Zoo

North Carolina Zoo was established in Asheboro, North Carolina, USA, in 1974. As a state-supported zoo, it is an agency in the Department of Natural and Cultural Resources. While the state provides an operating budget, the North Carolina Zoological Society is a non-profit partner that raises funds for conservation programs, capital campaigns, and other initiatives through memberships, donations, special events, gift shop sales, and other fundraising activities. NCZ welcomes up to one million guests each year. NCZ was established as the world's largest natural habitat zoo to provide large spaces for animals in natural settings. With this goal, the developed portion of NCZ containing exhibits and support structures (200 ha) was placed on a large tract of land surrounded by over 400 ha of natural land on Purgatory Mountain (Figure 1). Early explorers suggested that the region was occupied by Waxhaw, Sugeree, Saponi, Saura, Wateree, and/or Catawba native peoples

that were displaced by the influx of Europeans by 1750 [14]. More recently, the property was used for mining activities, and according to local lore, Purgatory Mountain was used as a liquor distillery and named for the numerous fires dotting the hillside during bootlegging operations [14]. NCZ houses more than 1700 animals representing North America and Africa, with construction of a new Asia exhibit currently underway. While NCZ has always been committed to the conservation of wildlife and their natural habitats, this focus has grown steadily over the years through the expansion of conservation and education programs supported by increased funding and staff positions. Funding increased from USD 248,000 in 2007 to USD 1.1 million in 2021. The Conservation, Education, and Science section of NCZ currently comprises 18 permanent staff, including five staff dedicated primarily to conservation and research. Animal management staff also strongly contribute to regional and international conservation programs, and additional support is provided by many seasonal staff, interns, AmeriCorps members, and volunteers.

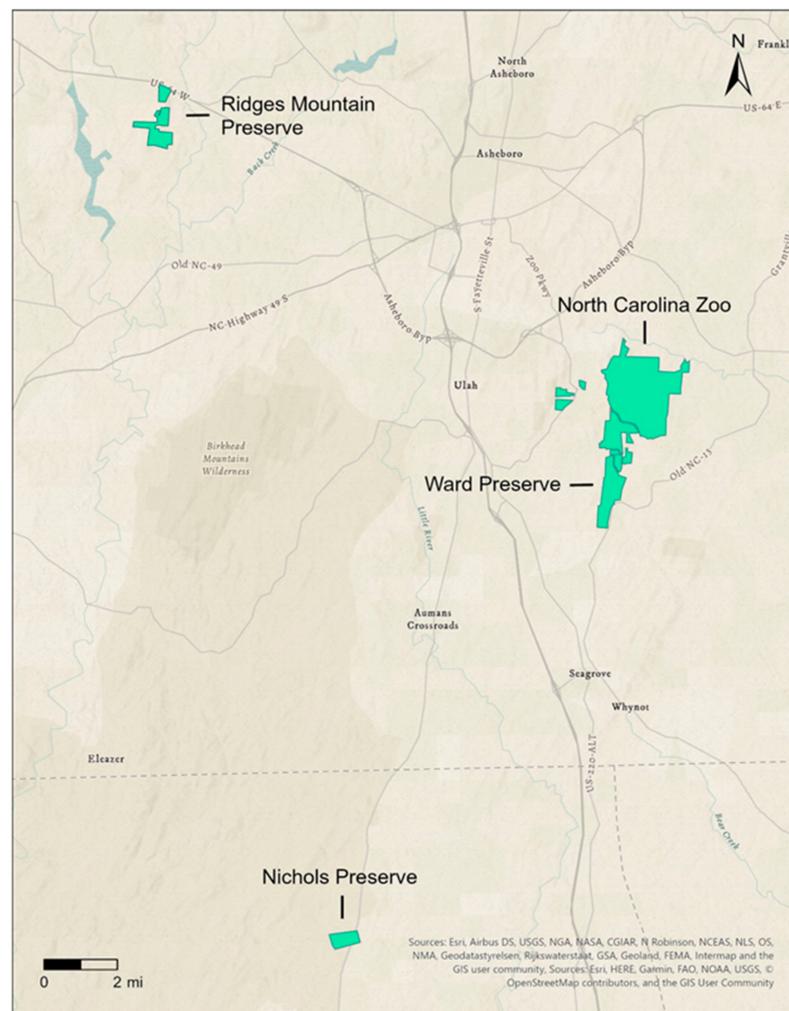


Figure 1. North Carolina Zoo plays an important role in land conservation by protecting and managing more than 800 ha of undeveloped land in central North Carolina. This includes land on and surrounding NCZ's main property and three off-site nature preserves: Nichols Preserve, Ridges Mountain Preserve, and Ward Preserve. The shaded region to the west of NCZ is the Uwharrie National Forest (containing the Birkhead Mountains Wilderness), which is the largest public landholder in the region.

3. Land Conservation and Management

3.1. Overview

Biodiversity is under threat worldwide and protected natural areas are widely recognized for their value in biodiversity conservation [15,16]. Because the greatest threats to biodiversity are landscape modification and fragmentation, the most effective protected areas preserve large contiguous tracts of high-quality natural communities [17,18]. While many protected areas are established to protect rare species or communities, common species also benefit from land protection and are often present in higher densities and demonstrate greater temporal stability [19]. Common species provide vital ecosystem processes and are useful indicators of ecosystem function and health [20,21]. In addition to supporting biodiversity, many natural areas also provide benefits for people, especially areas that provide recreational trails. Hiking and other outdoor activities provide opportunities for people to improve their mental and physical health and develop a deeper appreciation and sense of stewardship for protected natural areas [22–24].

North Carolina Zoo plays an important role in land conservation by protecting and managing more than 800 ha of undeveloped land in central North Carolina (Figures 1 and 2). NCZ is located in a rural area approximately 11 km from the city of Asheboro, which has a population of 25,000 people. The majority of public land in the region is part of the Uwharrie National Forest (20,860 ha), with most remaining land under private ownership. There is ongoing loss, degradation, and fragmentation of natural habitat in the region due to agriculture and urban development. The natural areas protected by the NCZ encompass a diversity of ecosystems and protect unique biological, geological, and cultural features. They also provide unfragmented spaces and movement corridors that allow wildlife to safely navigate the landscape. NCZ was established on a large tract of land surrounded by over 400 ha of natural land on and around Purgatory Mountain (285 m) at the northern edge of the Uwharrie range. This land supports a diversity of natural communities, including some that are rare in the region, such as upland pools that provide valuable breeding sites for amphibians, such as the four-toed salamander (*Hemidactylium scutatum*), which is species of special concern in North Carolina. Because of its size and habitat heterogeneity, this natural area provides important wildlife habitat, especially for forest interior species that require large areas of unfragmented forest.

NCZ expanded its land conservation footprint from its original property by acquiring additional land in the vicinity to create three off-site nature preserves. Ridges Mountain Nature Preserve (Ridges Mountain Preserve, 75 ha, established in 2000) protects Ridges Mountain (256 m) in the northernmost range of the ancient Uwharrie Mountains. The geology of Ridges Mountain is striking because of the enormous boulders, up to 15 m in height, that are found along the ridge line. In addition to preserving unique geology, Ridges Mountain Preserve protects high-quality mature forests and wetlands, and supports an assemblage of uncommon plant species, such as fragrant sumac (*Rhus aromatica*), due to basic soil that differs from the more typical acidic soils in the region. On a landscape scale, Ridges Mountain is also significant due to its connectivity to other large, forested areas along an upland to bottomland corridor. The Selma Cornelison Ward Nature Preserve (Ward Preserve, 131 ha, established in 2010) provides mature hardwoods along Bachelor Creek. This preserve protects a forested corridor between other forested areas in the region, including NCZ's main property, and it buffers the headwaters of the creek, supporting water quality and flow downstream. The Margaret J. Nichols Longleaf Pine Forest Preserve (Nichols Preserve, 47 ha, established in 2011) protects the largest remaining known stand of old-growth longleaf pine (*Pinus palustris*) in the Piedmont of North Carolina, containing trees that are more than 200 years old. The longleaf pine ecosystem, which is one of the most biodiverse ecosystems on the planet and contains many endemic species, has declined by more than 97% across its range in the southeastern USA [25].



Figure 2. North Carolina Zoo plays an important role in land conservation by (A) protecting ecologically significant lands, including this upland pool that provides important breeding habitat for amphibians, and by (B) managing these lands to maintain or improve their quality, such as by applying prescribed fire to this longleaf pine forest in partnership with the North Carolina Forest Service.

3.2. Land Protection

NCZ focuses on protecting larger tracts of unfragmented land that support high-quality natural communities (Figure 2A). Valuable partnerships with other state agencies and local non-profit organizations have assisted with identifying and facilitating the protection of ecologically significant land. The North Carolina Natural Heritage Program (NCNHP) collects and shares information about rare species and natural communities that is needed to evaluate the ecological significance of natural areas and potential ecological impacts of conservation and development projects. County-level natural area inventories conducted by the NCNHP were key in identifying the high-quality natural communities present on NCZ's main property and those protected on the three off-site nature preserves.

Once ecologically valuable lands were surveyed and identified, partnerships with the Three Rivers Land Trust and Piedmont Land Conservancy were key in locating land in need of protection and facilitating their acquisition. NCZ and Three Rivers Land Trust worked together to protect the land that became the Nichols Preserve. NCZ acquired half of the property by obtaining grant funds through the North Carolina Natural Heritage Trust Fund, which was established to preserve natural areas and rare species across the state.

The Three Rivers Land Trust purchased the other half of the property using interest-free loan funding through the Norcross Wildlife Foundation, and then worked with NCZ to obtain additional funds from the North Carolina Natural Heritage Trust Fund to sell the remainder of the property to NCZ. Piedmont Land Conservancy provided support and funding for acquiring the Ridges Mountain Preserve, along with funding provided by the landowner, Mary and Elliot Wood Foundation, Cannon Foundation, Kathleen Price Bryan Family Fund, Hans Klausner Foundation, and the North Carolina Natural Heritage Trust Fund. Piedmont Land Conservancy also provided legal assistance for acquiring the Ward Preserve, which was purchased using grant funding from the North Carolina Natural Heritage Trust Fund.

3.3. Land Management

Effective land management is essential for successful habitat and species conservation. NCZ manages natural areas to maintain high quality or increase quality where possible. The partners involved with acquiring NCZ's preserves continue to be involved with management planning, while NCZ serves as the steward and implements the land management plans. Detailed management plans have been written for all natural areas that include the history, significance, goals, and current and planned management practices. Several biological consultants have been instrumental in assisting with land management planning and support, particularly on the Nichols Preserve. An independent consultant, Terry Sharpe (Certified Wildlife Biologist and NC Registered Forester), created a detailed management plan for restoring the degraded old-growth longleaf pine forest on the site. Eli Beverly and Associates, LLC, has provided significant advice and expertise in managing invasive plant species.

While NCZ staff conduct routine maintenance in natural areas, such as mowing around parking areas and clearing hiking trails, more intensive management is conducted through partnerships. One example is prescribed fire, which is a management tool used to maintain and improve fire-adapted communities, such as the longleaf pine forest on the Nichols Preserve. NCZ partners with the North Carolina Forest Service to conduct prescribed burns on this site and other NCZ properties (Figure 2B). Trained burn crews with the North Carolina Forest Service carefully plan and conduct prescribed burns by considering safety, weather, and management goals. NCZ also works with volunteers to accomplish other management activities on natural areas, such as invasive plant control and litter cleanups.

NCZ staff conduct regular surveys and research studies to assist with conservation and management planning. This includes surveying plant, bird, mammal, amphibian, reptile, and invertebrate communities to inventory rare species and monitor populations over time. For example, one study documented the species diversity, seasonal activity, ecology, biomass, and demographics of the wild snake community at NCZ [26]. Biologists from the NCNHP assist with monitoring target species and provide expertise on managing for them. NCZ also facilitates research by universities by providing access to natural areas. Some completed projects include a study of longleaf pine (*Pinus palustris*) growth and morphology [27] and a study on the geographical distribution of lichens [28]. NCZ also participates in the Greater Uwharrie Conservation Partnership, which is made up of government agencies and private organizations that work together for the long-term conservation and enhancement of biological diversity and ecosystem sustainability in the Southern Central Piedmont region of North Carolina. The partnership meets regularly to share information and collaborate on projects and grants. By working together, partners increase the efficiency and effectiveness of conservation work in the region.

4. Collaborative Conservation of Declining Amphibians

4.1. Overview

Although the North Carolina Zoo works to protect many taxonomic groups, there is a strong focus on the conservation of declining amphibians in North Carolina. Globally,

amphibians are more threatened, and are declining more rapidly, than either birds or mammals, with over one-third of all species threatened with extinction [29]. North Carolina is a hotspot for amphibian diversity, with nearly 100 species, including more salamanders than any other region in the world [30], largely because of its diversity of habitats that range from mountain streams to coastal swamps. Unfortunately, many of North Carolina's amphibian species are in decline, mainly due to habitat loss and degradation.

NCZ works on collaborative projects with the North Carolina Wildlife Resources Commission (NCWRC) to bolster populations and improve habitats for target species (Figure 3), including the state-endangered gopher frog (*Lithobates capito*) and the eastern hellbender (*Cryptobranchus alleganiensis*), a species of special concern in North Carolina. Gopher frogs are specialists of the longleaf pine ecosystem, which has disappeared across its range in the southeastern USA [25]. Gopher frogs have declined with their habitat, and the number of populations in North Carolina has decreased from more than 50 to fewer than eight remaining in fragmented areas in southern and southeastern North Carolina [31]. Hellbenders are large, aquatic salamanders found in cool, clean, mountain streams in North Carolina that are threatened by degraded water quality and sedimentation that disrupts microhabitats [32].



Figure 3. North Carolina Zoo works on collaborative projects with the North Carolina Wildlife Resources Commission (NCWRC) to protect declining amphibians. (A) Here, NCWRC technician Mike Martin releases a gopher frog that was headstarted at the Zoo into a stump hole, and (B) Zoo and NCWRC staff use a hot water pressure washer system to control invasive red imported fire ant colonies to improve habitat for gopher frogs and other species.

Although this section focuses on collaborations for two target amphibian species, NCZ staff also participate in other herpetofaunal surveys across the state with the NCWRC and North Carolina State Parks (NCSP), and they are involved with the North Carolina Partners in Amphibian and Reptile Conservation (NCPARC), which is the local chapter of the Partners in Amphibian and Reptile Conservation (PARC). Such partnerships have proven successful as most organizations do not have sufficient staffing, resources, or experience to achieve long-term success alone. Experience across disciplines, coupled with regular planning and communication, have been paramount to the development of these efforts.

4.2. Population Augmentation

Translocations, which are the intentional movement of individuals or populations across landscapes, have played important roles in the conservation of many species, including amphibians [33–35]. One increasingly used translocation action is population augmentation, which occurs when a declining population is supplemented with individuals from another population [36]. The goal of population augmentation is to build a sustainable population that is resistant to demographic or environmental stochasticity [37,38]. Such population augmentation efforts are long-term endeavors due to numerous abiotic and biotic factors associated with survival and reproduction.

In 2016, NCZ began a collaboration with the NCWRC to augment the declining gopher frog population in the Sandhills region of North Carolina through a headstarting project (Figure 3A). Headstarting is a conservation technique, in which early-stage animals are raised to later life stages in artificial habitats before being released into natural habitats. The goal of headstarting is to increase survival rates from early to later life stages by keeping individuals safe from predators, habitat degradation, and environmental factors. As part of the collaborative effort for headstarting gopher frogs, NCWRC staff collect gopher frog eggs following breeding events and transport them to NCZ. Once the eggs hatch, the tadpoles are reared in outdoor mesocosms until metamorphosis. All newly metamorphosed frogs are measured and marked with Visual Implant Elastomer (VIE) so that they can be identified if they are later observed in the wild. After the frogs are processed, NCZ and NCWRC staff release the frogs into their natural habitat, either near the pond where the eggs were collected (2016–2019) or a nearby restored pond (2020–2022). The husbandry protocol is evaluated each year and adjusted based upon metamorphosis size and percentage of metamorphosed gopher frogs released (Table 1). A similar protocol has also been used on a trial basis to headstart the state-endangered ornate chorus frog (*Pseudacris ornata*) and the eastern tiger salamander (*Ambystoma tigrinum*).

Table 1. Summary of gopher frog headstarting efforts at NCZ from 2016 through 2022. This includes the number of wild egg masses (all collected in early spring, except for 2018, which included fall and spring collections), total number of recently metamorphosed frogs released, the percentage of frogs that survived to metamorphosis and were released, and mean snout-vent length (SVL; not measured in 2016) and mean mass of released frogs. Because of a lack of wild breeding in 2022, all headstarted and released frogs that year were the result of assisted reproductive methods used with frogs housed in NCZ’s collection.

Year	Egg Masses	Frogs Released	% Frogs Released	Mean SVL (mm)	Mean Mass (g)
2016	34	266	35	NA	5.7
2017	9	156	78	39.8	7.9
2018 (spring)	3	41	42	38.8	7.4
2018 (fall)	22	170	85	38.2	8.0
2019	19	162	81	37.0	7.2
2020	23	298	75	37.4	8.6
2021	16	459	70 *	34.4	6.2
2022	NA	113	91	34.4	6.4

* Excludes 50 non-releasable frogs removed from the project due to abnormalities.

In 2022, weather patterns hindered many of the winter breeding amphibians in North Carolina and there were no documented reproductive events by gopher frogs in the state. Because there were no eggs to headstart, NCZ and visiting partners from Mississippi State University used assisted reproduction techniques to successfully breed adult gopher frogs in NCZ's managed collection. Although this protocol has been used for gopher frogs and other species elsewhere, it was the first time that in vitro fertilization was used successfully to produce fertile gopher frog eggs in North Carolina. These eggs were raised at NCZ and resulted in the release of over 113 gopher frogs into the Sandhills that year, contributing to 1665 gopher frogs released at two ponds during the seven years of the program (Table 1).

Our monitoring efforts for gopher frogs focus primarily on acoustic monitoring and egg mass surveys because gopher frogs are secretive animals that spend more of their lives underground and are rarely seen outside of the breeding season when they migrate to ponds [39,40]. In the extremely rare event that a gopher frog is encountered outside a breeding pond, it can be visually examined for VIE. During the first four years of the headstarting program, frogs were released at the source pond in which the eggs were collected. Acoustic monitoring and egg mass surveys were conducted throughout the breeding season, and a subset of released frogs were also monitored using radiotelemetry to examine their patterns of movement, behavior, and survival. Many tracked frogs appeared to have been preyed on by red imported fire ants (*Solenopsis invicta*), an introduced species that occurs in high densities at this site. Although survival of juvenile gopher frogs is expected to be low (e.g., 12.5% during the first month; [41]), the threat posed by fire ants led to the development of a plan by NCZ and the NCWRC to control fire ants around this pond (see "Habitat Management" Section below).

Starting in 2020, we began releasing all frogs at a different pond that was recently restored by the NCWRC, but had no records of gopher frog breeding. Acoustic monitoring and egg mass surveys have been conducted throughout each breeding season since releases began. Gopher frog breeding has not yet been recorded at the restored pond, but this is not unexpected because gopher frogs can take several years to mature and only breed under specific weather conditions that do not occur every year. For example, no documented gopher frog breeding occurred anywhere in North Carolina during the spring 2022 breeding season. In collaboration with the NCWRC, our goal is to produce a sustainable population at the restored pond, but it may take many years of headstarting and monitoring to reach this goal due to numerous biotic and abiotic factors associated with survival and reproduction. Without appropriate seasonal rainfall to fill breeding pools and trigger breeding events, frogs may not be encountered for years.

4.3. Habitat Management

For translocations to be successful in building sustainable populations, any threats that caused their decline or could lead to further decline must be addressed [42]. For gopher frogs in the Sandhills population, a serious threat to their survival is invasive red imported fire ants, which can directly kill gopher frogs and other species with their potent venom. There are very high densities of fire ant colonies surrounding the main breeding pond, and many interactions between frogs and ants have been observed, including high predation rates of juvenile gopher frogs monitored using radiotelemetry. To mitigate this severe threat, NCZ and the NCWRC jointly developed a management plan to control fire ants and support gopher frog augmentation efforts. Following the methods of Tschinkel and King [43], the team used a large (1136 L) hot water pressure washer system to treat fire ant colonies (Figure 3B). Since 2020, more than 1200 colonies have been treated in this ongoing project. The treatments have been successful in eliminating some ant colonies; however, the success in reducing fire ant densities on the landscape is under evaluation. Overall, this collaborative project aims to benefit a genetically valuable population of gopher frogs, and the management implications will be applicable throughout the southeastern USA, where red imported fire ants negatively impact populations of many species of amphibians and reptiles.

A second collaborative project among NCZ, the NCWRC, and NCSP aims to benefit hellbender populations by improving habitat through the installation of artificial nest boxes. These boxes are designed to mimic rock crevices and provide nesting habitat and shelter in rivers lacking sufficient breeding sites. There are multiple designs used throughout the range of both the eastern and Ozark hellbender subspecies. However, despite nest boxes being extremely useful in Virginia, Ohio, and other parts of the hellbender's range, those used in North Carolina have been considered less successful because of little to no occupancy and lack of breeding success. NCZ is working with the NCWRC and NCSP to test hellbender nest box occupancy along stretches of the New River, where hellbenders have been monitored by NCSP staff and volunteers for over 10 years. Although this population seems to be stable, numerous populations of hellbenders in North Carolina have declined since 2010, by as much as 50% (John Groves, NCZ retired, and Lori Williams, the NCWRC, personal communication). The goal is to develop successful methods for installing and managing hellbender nest boxes in North Carolina by monitoring these boxes in sites with known hellbender populations so that these methods can be applied to other sites to benefit hellbender populations.

To date, NCZ has installed more than 40 nest boxes at two sites within the known range of hellbenders in North Carolina. Efforts at the first site were not effective after three years, primarily due to stochastic weather events and heavy river flow. Due to these factors, the boxes were moved to the New River State Park in 2020 as part of this new collaboration. While we have not documented occupancy at either site, the flow of the New River has been less impactful on box placement, and multiple crayfish and fish species have been documented using the boxes. We collect standardized data during each monthly survey during warmer months, which includes recording river width, flow rate, depth, and water quality, so we can make comparisons with other sites to examine nest box efficacy.

5. Wildlife Rehabilitation

Wildlife rehabilitation is the care of sick, injured, orphaned, and displaced animals for return to their natural habitat. Rehabilitation is provided to animals that have been orphaned due to human intervention or developmental abnormalities; sick animals exposed to toxins or carrying parasites or pathogens; injured animals that have experienced trauma due to collision (e.g., with windows and vehicles), entrapment/entanglement, or injury by another animal or human; and animals that have been displaced through habitat loss (e.g., tree removal, construction, and natural disturbances) [44–46]. Because cases are usually related to anthropogenic activity, the purpose of wildlife rehabilitation is to offset human impact and to mitigate human–wildlife conflict [47]. The value of wildlife rehabilitation is multi-fold, from ensuring native animals are cared for by experienced and equipped rehabilitators, to educating the public about wildlife, to engaging the community in assisting with the care of wildlife. Wildlife rehabilitation has conservation and scientific purposes as well. For example, rehabilitation has been instrumental in disease surveillance [48–51]) and providing a better understanding of the natural history and needs of species while in human care. In addition, by providing people with close contact with wildlife, rehabilitation can increase knowledge and respect of local wildlife and the threats they face, which can contribute to biodiversity conservation.

North Carolina Zoo's Wildlife Rehabilitation Center (Center) opened in August 2001 as a community resource for assisting with local wildlife in need of veterinary and rehabilitative care (Figure 4). The Center's goal is to offset human impact and inspire and educate people about native wildlife. The Center provides free, professional veterinary and rehabilitation services to sick, injured, and orphaned native North Carolina animals found in the wild for the sole purpose of returning them to the wild in a condition that will optimize their chances of survival after release. The Center performs euthanasia when injuries are too severe for animals to live a quality life. The Center admits 800–1000 animals per year, representing over 100 species. Most species admitted are common because these are most likely to be encountered by the public. These include birds common in resi-

dential and urban areas (e.g., songbirds, woodpeckers, and doves), eastern gray squirrels (*Sciurus carolinensis*), eastern cottontails (*Sylvilagus floridanus*), Virginia opossums (*Didelphis virginiana*), and eastern box turtles (*Terrapene carolina*; Figure 4A). In addition, the Center has rehabilitated uncommon species, such as bald eagles (*Haliaeetus leucocephalus*), and protected species, including wood storks (*Mycteria americana*), piping plovers (*Charadrius melodus*), timber rattlesnakes (*Crotalus horridus*), and diamond-back terrapins (*Malaclemys terrapin*). Rehabilitation can play an important role in species conservation, especially for long-lived species with population declines that are difficult to detect, such as eastern box turtles that take up to 10 years to reach sexual maturity and can live for 50–100 years or more [52]. Most frequently, animals are admitted due to vehicular collisions, injuries caused by domestic cats, window collisions, and unnecessary intervention of presumed orphans. The Center is uniquely qualified to care for species with specialized needs as it has the resources of NCZ, including licensed rehabilitators, board-certified veterinarians, expertise of NCZ staff, and facilities that most independent wildlife caretakers and clinics do not have at their disposal. This includes a large variety of enclosures, shift cages, aviaries, and outdoor “wilding” or “pre-release” conditioning habitats that meet or exceed standard guidelines [53].



Figure 4. The North Carolina Zoo’s Center for Wildlife Rehabilitation provides professional veterinary and rehabilitation services to sick, injured, and orphaned native wildlife, such as (A) this eastern box turtle being treated by a veterinary student and intern, and (B) this orphaned black bear cub reared through a partnership with the North Carolina Wildlife Resources Commission.

Initially, the Center was staffed by volunteers, with care overseen by NCZ's veterinary staff, but as the caseload increased as local residents became aware of the Center and services provided, there was a need for onsite staff. Consequently, a veterinary technician was hired to manage Center operations in 2007. Since then, the Center has grown to include two full-time staff members, three seasonal staff members, a well-established and reputable internship program, a stable volunteer program, and visiting veterinary students from North Carolina State University's Cummings School of Veterinary Medicine. The Center trains interns, volunteers, and veterinary students in respectful and responsible wildlife rehabilitation methods using the most up-to-date and science-based practices. Since its inception, the Center has hosted over 60 interns from more than 25 states. The internship program includes a weekly curriculum that is accredited by the International Wildlife Rehabilitation Council and hands-on opportunities working directly with wildlife with training and supervision from Center staff.

In addition to providing rehabilitative care, the Center also participates in research. Post-release survival studies have been conducted on rehabilitated birds since 2012 that are banded with metal bands issued by the United States Geological Survey and approved sequences of color bands to make sure each bird is individually recognizable from a distance. This study focuses on five species: blue jays (*Cyanocitta cristata*), Carolina wrens (*Thryothorus ludovicianus*), mourning doves (*Zenaidura macroura*), northern cardinals (*Cardinalis cardinalis*), and red-bellied woodpeckers (*Melanerpes carolinus*). The Center initially partnered with Guilford College to initiate the study and later acquired permits to continue the study independently [54]. As part of this ongoing study, birds were admitted to the Center at fledging stage or younger and cared for until they were released at the appropriate stage. All birds were released outside the Center by placing them in a soft-sided enclosure with perches that was hung at the release site for a minimum of 30 min and then unzipped, allowing the birds to fly out on their own. Birds were resighted opportunistically and evaluated according to an ethogram to assess whether released birds were behaving similar to their wild, parent-reared counterparts or behaving inappropriately due to their time in human care. Between 2012 and 2022, 320 birds were banded as part of this ongoing study evaluating the success of hand-reared birds. Of these birds, 42 (13.1%) were resighted at least once and up to 327 times. Birds survived up to 6.3 years post-release and the average number of days to the last resighting was 243 days. All resighted birds demonstrated normal wild behavior that was indistinguishable from their wild counterparts.

As part of a collaboration with the NCWRC that began in 2015, the Center rears orphaned black bear (*Ursus americanus*) cubs (Figure 4B) and assists biologists with fitting the cubs with GPS collars so they can be tracked after they are released to study their movement and behavior. The Center is one of two facilities in the state approved by the NCWRC to rear black bear cubs because the Center can provide a large, safe space for them to grow and is committed to rearing cubs in a hands-off manner, as much as possible. Preliminary data from this ongoing study suggest that the behavior and survival of released bears appears similar to those of wild-reared bears and the majority have not become nuisance bears.

The need for better rehabilitation programs for North American river otters (*Lontra canadensis*) has also led to a partnership with the North Carolina Aquariums. River otters are intelligent and inquisitive, and they can readily habituate to caregivers during hand-rearing. As they age, they must have access to deep water pools to learn to swim and catch fish and disassociate with humans. The North Carolina Aquariums often receive calls about orphaned otter pups, and they will assess whether they can be reunited, need to be rehabbed, or need to be placed under permanent human care. If rehabilitation of otter pups is warranted, the Center will step in to assist with rearing.

The Center has assisted thousands of North Carolina residents with wildlife in need by advising callers with concerns about wildlife, admitting and caring for wildlife in need of veterinary or rehabilitative care, training interns and volunteers about wildlife husbandry and medicine, and educating other rehabilitators through conference presentations and

networking. When animals have a poor prognosis for recovery, the Center provides euthanasia and the carcasses can be used for educational purposes, either for scientific study or training individuals in veterinary care. Through numerous partnerships, NCZ's Wildlife Rehabilitation Center has become a vital community resource in engaging people to protect wildlife and wild places.

6. Outreach and Sustainability

6.1. *Connecting People with Nature*

Hiking trails connect people with nature and improve their physical and mental health, while benefitting the environment and local economies [22–24,55]. North Carolina Zoo has long embraced the idea that trails are one of the best ways to introduce people to nature. Because of this mindset, NCZ openly advocates for trails, both on NCZ property and in the region. Since 2019, NCZ has been a partner in the Randolph County Trails Advisory Commission. This partnership includes representatives from nine municipalities across the county, as well as other representatives that have an interest in promoting outdoor activities and protecting natural and historical areas. Together, this group advocates for trail expansion and protection of natural and cultural resources by sharing information, applying for grants to acquire property and build trails, and planning and completing these projects.

NCZ builds and maintains sustainable hiking trails that protect sensitive plants and animals while providing opportunities for hikers to explore natural features on NCZ's main property (Purgatory Mountain) and Ridges Mountain Preserve. NCZ currently maintains approximately eight miles of trails and plans to build additional trails. Trails on Purgatory Mountain begin at NCZ's North America region parking lot and are open at no charge anytime NCZ gates are open, whereas trails at Ridges Mountain Preserve require hikers to notify NCZ before visiting. NCZ trails systems are among the most significant in the area, in terms of distances, interesting features, and usage by hikers. The Purgatory Mountain Trail System (8 km) is the second largest, behind the Birkhead Mountains Wilderness (24 km; Figure 1), whereas most other trails in the region are shorter in distance (<3 km) and tend to be in more urban areas. We have observed that the Purgatory Mountain trails are used daily during favorable weather by multiple groups of visitors, as well as NCZ staff enjoying a hike on their lunch break or before or after their shift. Most non-staff users are local, but others have traveled from farther locations within North Carolina or other states. The NCZ is often the main destination for these guests, but they extend their stay to hike on the trails while they are in the area. The internal Trail Team leads planning, construction, and maintenance of all trails, and assistance with trail work is provided through partnerships with local schools and other volunteer groups (Figure 5A). Partnerships with the Phi Theta Kappa Chapter at Randolph Community College and Future Farmers of America at Asheboro High School Zoo School have been especially important for completing trail work and engaging students during the COVID-19 pandemic when other service opportunities were suspended. NCZ naturalists lead regular nature hikes for public and private groups along the trails to explore the biodiversity and unique geologic features on the land.



Figure 5. North Carolina Zoo works on local outreach and sustainability projects with community partners to reduce impacts on natural resources and inspire guests and community members to get involved in conservation. This includes partnering with local schools to (A) build sustainable hiking trails on zoo-owned land and (B) plant trees on school grounds.

6.2. Combating Habitat Loss and Degradation

Habitat loss and degradation are the largest threats to biodiversity globally [17,18], and NCZ combats these threats by increasing habitat quality for native species on NCZ grounds and in the local community. Pollinators are important components of ecosystems [56], and NCZ promotes their conservation as a program partner in the AZA SAFE (Saving Animals From Extinction) North American Monarch program. One of the actions NCZ takes to enhance habitat for monarchs and other pollinators is planting Monarch Waystations and Pollination Stations. Monarch butterflies are threatened by habitat loss at overwintering

grounds in Mexico and throughout breeding areas in the United States and Canada [57]. The Monarch Waystation program, led by the organization Monarch Watch, promotes planting gardens that contain milkweeds and nectar plants to support larval and adult monarchs. NCZ maintains five Monarch Waystations on grounds that support monarchs and other pollinators and provide interpretive signs to educate NCZ guests about monarchs and their habitat requirements. We have observed monarch eggs and caterpillars on common milkweed (*Asclepias syriaca*) and swamp milkweed (*Asclepias incarnata*) in the gardens. Adult monarch butterflies and other pollinators, such as bees, moths, and other butterflies have also been observed using nectar plants in the gardens. These include bumblebees (*Bombus* spp.), carpenter bees (*Xylocopa* spp.), mason bees (*Osmia* spp.), hummingbird clearwings (*Hemaris thysbe*), and eastern tiger swallowtails (*Papilio glaucus*). NCZ has also partnered with five local schools and the Randolph County Public Library to support pollinators and educate community members by creating “Pollination Stations” at their locations. These container gardens are planted in upcycled containers provided by NCZ.

NCZ also supports songbird conservation as a program partner in the AZA SAFE North American Songbirds program. The goal of this program is to reduce threats to North American songbirds and secure sustainable wild populations of these species throughout their ranges by harnessing the collective strengths of zoos, aquariums, and partners through supporting education and on-the-ground conservation activities. One way that NCZ participates in this program is by keeping windows and other glass surfaces safe for birds. Up to one billion birds die from window collisions in the USA each year [58], making this the second largest threat to birds in the country (behind domestic cats). Research on bird-glass collisions has led to the development of several different types of commercially available products that reduce glass reflection and transparency and successfully reduce collisions [59–61]. NCZ has installed UV-reflective glass and patterned films on windows and other glass surfaces that are part of animal exhibits and viewing areas. Interpretive signs below these glass treatments educate NCZ guests about the threats of windows to birds and what they can do to help at home. NCZ is closely monitoring the effectiveness of these glass treatments. For example, when Feather Friendly® window markers were installed on a building containing many large, mirrored windows in 2021, bird collisions declined by 68% (from 38 to 12 strikes) during the year following mitigation when compared with the previous year. Another study observed a similar reduction in collisions (71%) after installing the same product [60].

A major environmental challenge is litter pollution, which can harm wildlife when they ingest it directly or indirectly, become trapped in it, or become drawn to roadsides and other dangerous areas where litter accumulates [62–64]. One way that NCZ combats this issue is by participating in the Adopt-A-Highway program, managed by the North Carolina Department of Transportation. Through this program, NCZ has conducted 5–6 cleanups per year for the last 25 years, removing thousands of pounds of trash from a two-mile stretch of roadway. NCZ also keeps cell phones and other small electronics out of natural areas and landfills by collecting them for recycling through the Gorillas on the Line program. This global program aims to increase recycling of cell phones and small electronics to protect habitats for gorillas and other wildlife in central Africa, where materials are mined. Furthermore, NCZ composts 2000 tons of waste annually, including animal manure and plant waste, in addition to food scraps and compostable plates, bowls, and cutlery from the onsite restaurants. The finished compost is used in NCZ’s horticulture operations.

6.3. Combating Climate Change

Climate change is a major threat to biodiversity, but accurate predictions and effective solutions are difficult to develop [65,66]. NCZ works with partners to combat climate change at the local scale by planting trees, promoting electric vehicles, and educating and empowering people to take action against climate change. Though a partnership with Polar Bears International as an Arctic Ambassador Center, NCZ works collaboratively

on research, education, and action programs that address climate change. Some of the programs implemented by NCZ as part of this partnership involve planting trees to increase sinks for atmospheric carbon. Over the last 12 years, NCZ has planted over 600 trees at schools, parks, and other public lands in the community, and distributed thousands of seedlings as part of Arbor Day and Earth Day celebrations (Figure 5B). Using a conservative estimate (10 tons of carbon dioxide sequestered per hectare by 1000 trees; [67]), we estimate that an average tree absorbs an average of 10 kg of carbon dioxide per year, and therefore, that the 600 trees we have planted absorb 6000 kg of carbon dioxide each year. In addition to their value in storing carbon, some of the trees were planted to absorb rainwater and mitigate erosion or to provide shade in heat islands, thereby providing other benefits to the environment and community.

NCZ installed a grid-connected photovoltaic solar array in 2008 called “Solar Pointe” as another initiative to combat climate change. Each of the three picnic shelters at Solar Pointe supports 297 square meters of photovoltaic panels, and together they can generate a maximum of 104 kilowatts of power per hour. These panels supply energy to the local power grid through partnerships with Carolina Solar Electric Company and the Randolph Electric Membership Cooperative (REMC). Solar Pointe is not capable of generating enough energy to fully operate NCZ (1.8 megawatts used per hour at peak operation), but the supply helps reduce the local demand for energy and avoid potential issues during extreme weather when demand could exceed supply. In addition, for each hour that Solar Pointe is generating energy at maximum capacity, 0.074 tons of greenhouse gas emissions are avoided, which is equivalent to burning 37 kg of coal. With an estimated 300 days of clear skies annually over fourteen years and a daily maximum generating time of four hours per day, Solar Pointe has avoided the use of 684 tons of coal. This is comparable to the energy required to heat and cool 17 residential homes for one year.

NCZ also reduces reliance upon petroleum products by using and promoting electric vehicles. There are currently 13 electric vehicles in NCZ’s vehicle fleet, and two electric buses have been ordered with grant funding from the North Carolina Department of Environmental Quality (NCDEQ). These vehicles produce no direct emissions, but they are charged by connecting to the local power grid. REMC receives 8% of energy from renewable sources (e.g., solar and wind), 2% from hydroelectric installations, and 54% from a nuclear power plant (Michael Trent, REMC, personal communication). Because nuclear power reactors do not produce direct carbon dioxide emissions, they are largely carbon neutral, although the overall impact of nuclear power on the environment is controversial. Because NCZ’s electric vehicles produce no direct emissions and a portion of the energy used to power them is carbon neutral, they operate more efficiently and with less air pollution than their gasoline or diesel counterparts. NCZ also provides electric vehicle chargers as a free service to guests to encourage electric vehicle use. This infrastructure was funded by a grant from NCDEQ. Annually, in collaboration with the Randolph Electric Membership Cooperative, NCZ hosts the annual Kickoff to National Drive Electric Week event. This event showcases the clean-air and cost-saving benefits of driving all-electric vehicles and plug-in hybrid vehicles. Through these initiatives and others, NCZ is committed to sustainability by reducing its impact and raising awareness about green practices.

7. Recommendations for Zoos

NCZ’s regional conservation programs have evolved over time and continue to develop in response to outcomes and conservation needs. NCZ is unique in some ways because it is surrounded by natural areas with high biodiversity and is supported by the state and a non-profit partner. However, there are many ways that other zoos, including urban zoos or smaller zoos with fewer resources, can contribute to local conservation efforts in meaningful ways. Many local initiatives are inexpensive or only require participation by staff or volunteers, since extensive travel is not required, unlike many international conservation efforts. Although many zoos do not own conservation lands, they can create wildlife habitat on their grounds by planting native vegetation that benefits wildlife and

pollinators, and avoiding planting non-native species that may cause ecological harm. Zoos can also partner with local state, county, or city parks by providing leadership and stewardship. For example, zoos can provide staff and volunteers to assist parks with planting trees, removing invasive plants, building trails, or cleaning up litter. Zoos could also partner with parks to lead public nature hikes or contribute to biodiversity monitoring. For example, Memphis Zoo partners with the Overton Park Conservancy in conducting stewardship, outreach, and research activities in the Old Forest State Natural Area, adjacent to the Memphis Zoo.

Zoos can also support regional conservation by participating in large-scale community science projects such as NestWatch or FrogWatch and contribute observations on biodiversity for use in science through platforms such as eBird and iNaturalist. If zoos are interested in playing a larger role in conservation efforts for local imperiled species, we recommend connecting with the state wildlife agency to discuss possible partnerships. Zoos often play an important role in headstarting and captive breeding programs because many have facilities and expertise for caring for animals before they are released into natural habitats. Examples include Woodland Park Zoo and Oregon Zoo's headstarting program for western pond turtles (*Actinemys marmorata*), and the captive breeding and release program for the eastern indigo snake (*Drymarchon couperi*) at the Orianna Center for Indigo Conservation, which is operated by the Central Florida Zoo and Botanical Gardens. Finally, zoos can provide important conservation messaging through signage and social media to educate others about wildlife and inspire actions they can take to conserve wildlife and their habitats. The AZA SAFE programs (e.g., SAFE North American Songbird and SAFE North American Monarch) provide useful resources for messaging, as well as recommendations for conservation initiatives that can be implemented at participating zoos.

8. Conclusions

Protecting biodiversity depends on the contributions of committed conservation organizations working together to solve complex challenges. The North Carolina Zoo works with partners across the state on projects that aim to protect local species and their habitats. NCZ plays an important role in land conservation by protecting and managing more than 800 ha of undeveloped land, and multiple partnerships have been key in identifying, acquiring, and managing these ecologically significant lands. NCZ also works on collaborative projects with the NCWRC to protect declining amphibians, including supporting gopher frog populations through headstarting and habitat management, and installing artificial nest boxes to provide nesting habitat and shelter for hellbenders. In partnership with the NCWRC and North Carolina Aquariums, NCZ's Wildlife Rehabilitation Center cares for wildlife in need of veterinary or rehabilitative care, with support from trained interns, veterinary students, and volunteers. NCZ also collaborates with numerous community partners on numerous outreach and sustainability initiatives, including building hiking trails, planting pollinator gardens and trees, keeping windows safe for birds, removing litter, composting, and installing solar panels and electric vehicle chargers.

Zoos are becoming leaders in conservation, research, and education as their role evolves over time. To address growing biodiversity losses and human impacts on the environment, collaborative efforts are needed to provide solutions that are effective, innovative, and long-lasting. As demonstrated through the conservation programs reviewed here, zoos can develop successful partnerships with local and state government agencies, academic institutions, non-profit organizations, other zoos and aquariums, schools, libraries, and businesses. Zoos can benefit these partnerships by contributing crucial resources and expertise that are needed to protect natural communities and the benefits they provide to humans. Through partnerships that aim to reduce their ecological footprints, zoos can benefit local and global ecosystems and play a lead role in setting new sustainability standards and serving as examples for other attractions and organizations.

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