FOREST REMOVAL AND THE CASCADE OF EFFECTS CORRESPONDING WITH AN OZARK HELLBENDER POPULATION DECLINE

Max A.Nickerson[1], Amber L. Pitt[2], Joseph J. Tavano[3], Kirsten A. Hecht[4], and Joseph C. Mitchell[1]

ABSTRACT

Populations of the endangered Ozark Hellbender salamander (*Cryptobranchus alleganiensis bishopi*) in the North Fork of the White River (NFWR) in Missouri and other streams have declined precipitously in recent decades. Deforestation of the riparian and nearby upland habitat has corresponded with in-river habitat changes and other interacting stressors that coincide chronologically with the precipitous decline. We review the cascade of effects, including changes in water quality, benthic habitat, illegal and scientific harvesting, and introduced and reintroduced species occurrence that followed deforestation in the context of their impacts on hellbenders and relationship with other stressors such as climate change. In-river habitat changes since the 1960s include benthic microhabitat alterations associated with redistribution of gravel, siltation, and sedimentation and, in part, increases in nuisance vegetation, including periphyton. Deforestation of riparian and nearby upland habitats increased access and opportunities for human activities such as recreation, wildlife collection, and development. The subsequent degradation of stream habitat and water quality following deforestation reduced the carrying capacity for the NFWR Ozark Hellbender population and had negative consequences on population health.

Key words: conservation, *Cryptobranchus alleganiensis bishopi,* deforestation, Ozark Hellbender, salamanders, sedimentation, river.

ISSN 2373-9991

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Nickerson, M. A., A. L. Pitt, J. J. Tavano, K. A. Hecht, and J. C. Mitchell. 2017. Forest removal and the cascade of effects corresponding with an Ozark Hellbender population decline. Bulletin of the Florida Museum of Natural History 54(10):147–164.

INTRODUCTION

Hellbenders (*Cryptobranchus alleganiensis*) are long-lived, large-bodied, aquatic salamanders native to the eastern United States (Fig. 1). They typically occupy fast-flowing streams with high water quality and use large rocks for diurnal refugia and nesting habitat (Nickerson and Mays, 1973a; Foster et al., 2009). Hellbenders are excellent indicators of water quality due to their aquatic lifestyle, highly permeable amphibian skin, long life, and habitat associations (Nickerson and Mays, 1973a; Nickerson et al., 2003). Population declines throughout most of their range have been attributed to a variety of factors such as aquatic and terrestrial habitat degradation, disease, collection for scientific investigations and educational purposes, management practices, and poaching for the pet trade (Wheeler et al., 2003; Briggler et al., 2007; Nickerson and Briggler, 2007; Foster et al., 2009; Nickerson et al., 2011; Hiler et al., 2013).

The Ozark Hellbender (*Cryptobranchus alleganiensis bishopi*; Fig. 1) is a federally listed endangered species endemic to south-flowing streams in the Black and White River drainages in the Ozark region of southern Missouri and northern Arkansas in the United States (USFWS, 2016). The population located in North Fork of the White River (NFWR), Ozark County, Missouri, has been studied extensively since 1968 (Nickerson and Mays, 1973a; Bodinof et al., 2012). The landscape, especially the riparian or near riparian habitat, has undergone substantial land use and land cover change since initial surveys in 1968–1971. The NFWR population can serve as a long-term case study to examine the correlation between habitat changes and population decline. It is a reference for comparison with hellbender populations in other regions. In this paper, we compile and review

Figure 1. An Ozark Hellbender (*Cryptobranchus alleganiensis bishopi*) from North Fork of White River, Ozark County, Missouri. Photo credit: Jeff Briggler.

the myriad of studies available on the NFWR Ozark Hellbender population and its habitat. The studies we reviewed examined land use/land cover changes that included deforestation, development, and subsequent changes in Ozark Hellbender population size and structure (Nickerson and Mays, 1973a, 1973b; Wheeler et al., 2003), the riverine habitat and illegal and legal harvesting (Nickerson and Briggler, 2007), recreational use of the river and water quality (Nickerson and Mays, 1973a; Solis et al., 2007b; Nickerson et al., 2009; Pitt and Nickerson, 2012), flooding (Nickerson et al., 2007), and hellbender injuries and skin microbial communities (Hiler et al., 2005; Nickerson et al., 2011; Bodinof et al., 2011). We present a condensed picture of findings from these studies beginning with habitat changes coupled with forest removal during 1968–2012. We discuss factors postulated to have caused the decline of this population that may or may not be associated with deforestation (e.g., Wheeler et al., 2003; Trauth et al., 2004; Phillips and Humphries, 2005; Nickerson et al., 2011).

North Fork of the White River

The headwaters of the NFWR watershed are located within the Mark Twain National Forest (MTNF) in Missouri, USA. The watershed occupies approximately 3,597 km^2 of the landscape and is drained by two major streams, NFWR and Bryant Creek. NFWR is a seventh order stream that flows generally southward for 108 km before reaching Norfork Lake near Tecumseh, MO. Bryant Creek flows southeasterly for 114 km before emptying into the NFWR downstream from Dawt Mill, MO, located approximately 1 km upstream from Norfork Lake. The NFWR watershed is in the Ozark Soils Region. The geology is highly karst, comprised primarily of Ordovician and Mississippian limestone, sandstone beds, and 283 springs, including some of Missouri's largest (Miller and Wilkerson Jr., 2001). The NFWR has an average gradient of 2.42 m/km (Miller and Wilkerson Jr., 2001). In 2001, land use/land cover within the NFWR watershed was primarily forest/woodland (64.9%). with grassland/cropland (34.2%), and urban (0.4%) comprising the remainder. About 13% of the watershed is in public ownership, approximately 88% of which is managed by the United States Forest Service. Oak-hickory forests, sometimes with shortleaf pine (*Pinus echinata*) that typify forested sections of the watershed, are well adapted to the shallow soils of this region (Miller and Wilkerson Jr., 2001).

RESULTS

Surveys and Ozark Hellbender Population Estimates in the NFWR

In October 1968, we conducted a two-day pilot study in the NFWR to determine if the *C. a. bishopi* (Fig. 1) population merited an intensive research effort, and if so, where and how to structure the study. We observed no other people on the river during the pilot study. In 1969, we built a field camp and established a 4.6 km research section, which would become the most extensively surveyed section of the NFWR. We established our research section approximately midway between the southern margin of Mark Twain National Forest (MTNF) and the lentic habitat of Norfork Lake in northern Arkansas (Fig. 2). The area surrounding the research section was privately owned during this time. We divided the section into 50 subsections, each 92 m long. In 1969, we completed a mark-recapture study of hellbenders within the first 29 upstream sections (2.67 km) of the 4.6 km research section (Fig. 2). The population structure histogram from this study approximated a normal bell-shaped curve. We estimated a density of 428 individuals >12.0 cm total length (TL) per km, indicating a healthy population with recruitment (Nickerson and Mays, 1973a). We observed few injuries at that time (2.9% of 479 hellbenders); only one individual had a serious injury (Hiler et al., 2005; Nickerson et al., 2007). In 1970, we conducted a mark-recapture study in part of a riffle within sections 2 and 3 (i.e., riffle 2–3), which had deep chert-laden gravel beds. This survey yielded an estimated population of 269 resident individuals >12.0 cm TL (Nickerson and Mays, 1973a).

Larvae were difficult to find. Between 1969 and 1972, we found only 11-gilled larvae in a sample of 765 Ozark Hellbenders in the research section (Nickerson et al., 2003; Nickerson and Mays,

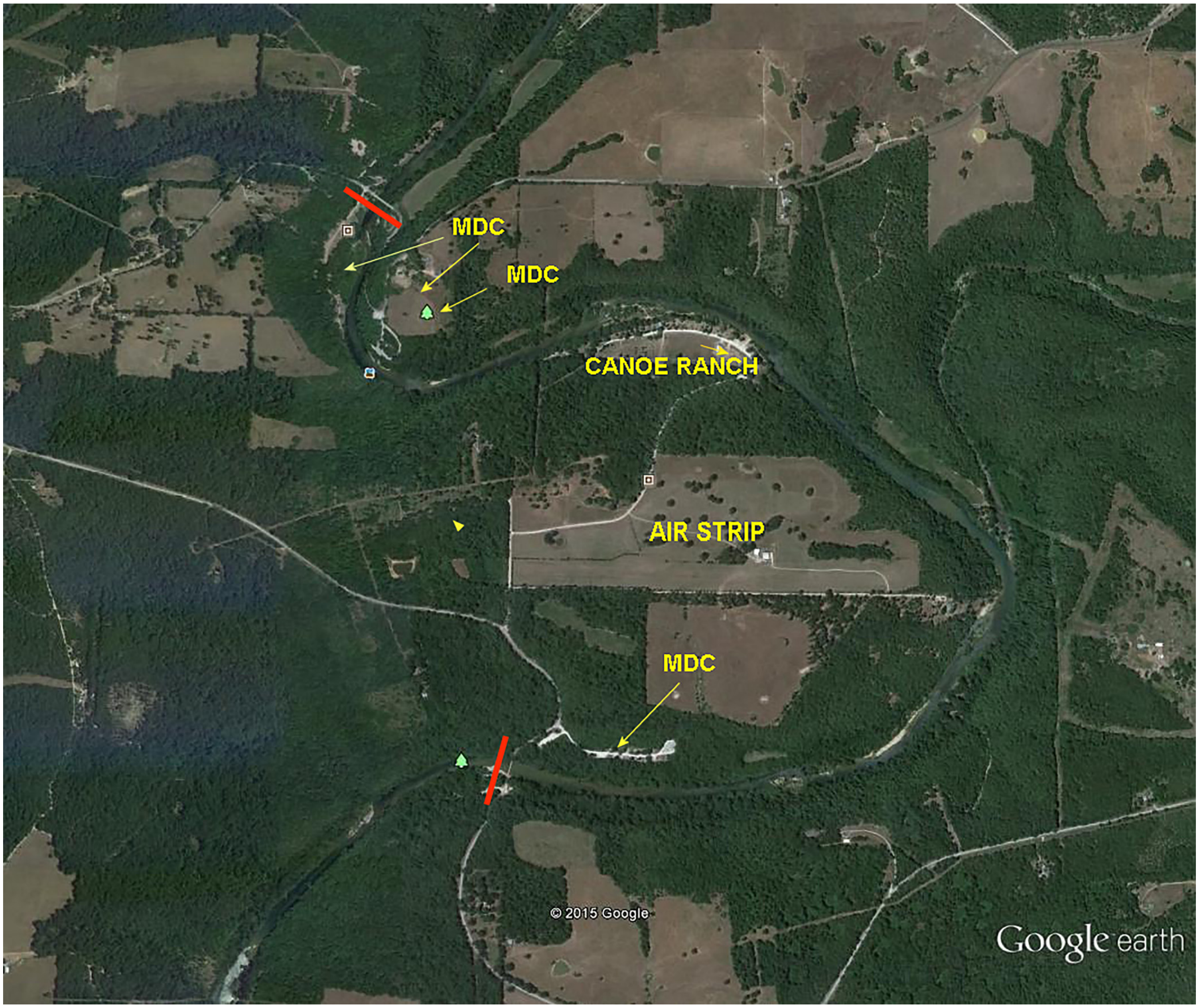

Figure 2. 2015 Google Earth photo showing the areas of forest removal and development in the North Fork of White River, Missouri, USA reseach section located between the two red bars (MDC=Missouri Department of Conservation). Map modified from Google Earth.

1973b). However, we rarely found larvae prior to recorded population declines in most studied populations, likely due to issues with detectability and survey methodology rather than lack of recruitment (Nickerson et al., 2003; Nickerson and Mays, 1973a; Peterson et al., 1983; Foster et al., 2009). We found larvae within interstitial gravel spaces and under smaller rocks under the larger rocks typically used by adults (Fig. 3). Ozark Hellbender surveyors seldom sampled interstitial spaces within gravel beds and shallow near-shore habitats (Nickerson et al., 2003). Population structure that exhibited multiple size and age classes at the time of the early surveys indicated that recruitment was occurring (Nickerson and Mays, 1973a; Nickerson et al., 2003).

Between 1968 and 1980, we conducted a total of 169 days of skin-diving surveys in the NFWR research section and often areas above and below. We conducted surveys in every month, although not every month of every year (Nickerson et al., 2007). Peterson et al. (1983) conducted a

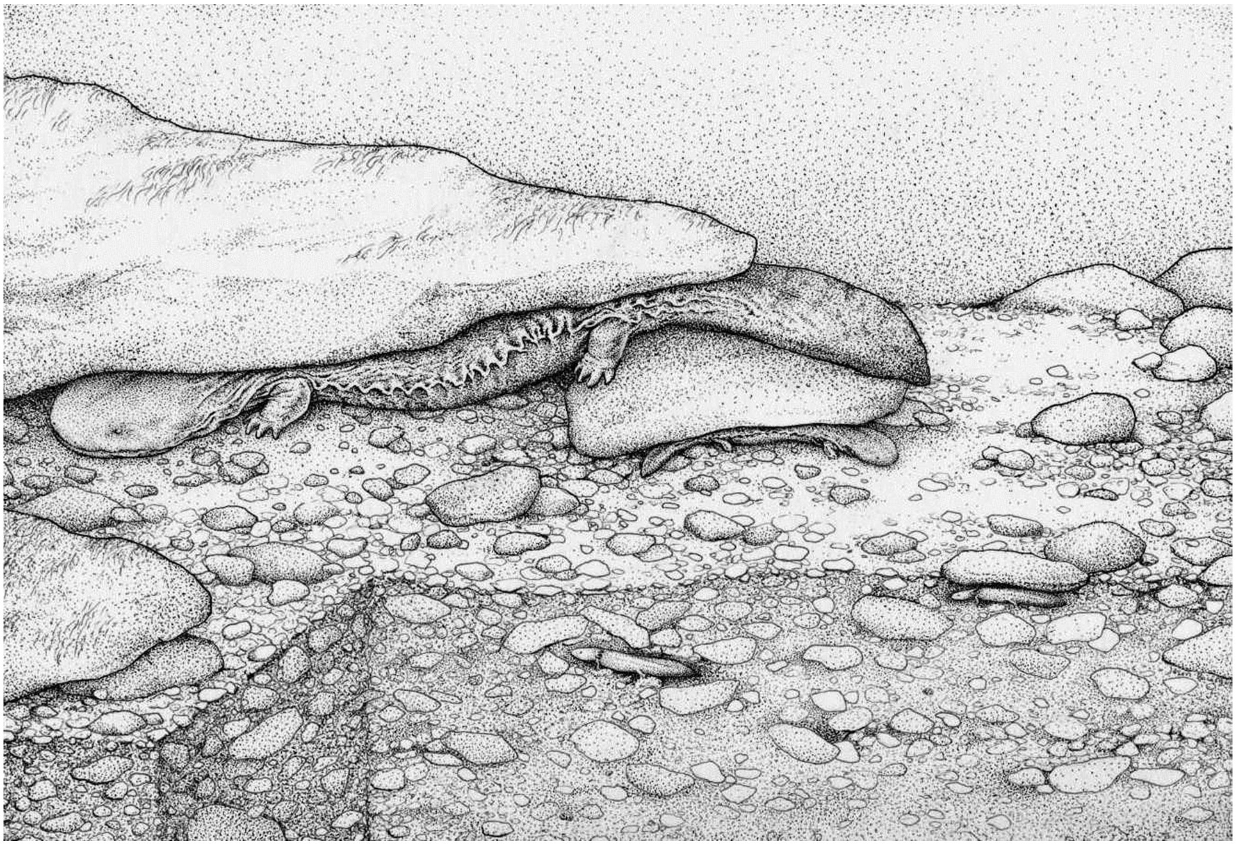

Figure 3. Locations of Ozark Hellbender (*Cryptobranchus alleganiensis bishopi*) larvae in a North Fork of White River, Missouri, USA chert gravel riffle. Illustration credit: Jason Bourque.

"wade and rock turning" population survey in 1977–1978 which included some portions of our research section and the entire reach of riffle 2–3. Their study estimated a large population of 744 individuals. Their riffle 2–3 population estimates fell within the 95% confidence limits (one per 6–7 m^2 to one per 13–16 m^2) of estimates we obtained in 1970 (Peterson et al., 1983).

In 1998, Wheeler et al. (1999, 2003) conducted rapid surveys of a variety of river sections within five Missouri rivers, including NFWR, and estimated that Ozark Hellbender populations had declined an average of 70%. They showed a disproportionate decrease in numbers of smaller individuals which they interpreted as lack of recruitment. Furthermore, they routinely observed injuries and abnormalities among adults. J. Briggler (in Nickerson et al., 2011) observed injuries on 26 of 55 individuals (47%) captured in 2005. Blood samples taken from *C. a. bishopi* (n = 33) in NFWR and Eleven Point Rivers and *C. a. alleganiensis* (n = 45) from Davidson River-Looking Glass Creek, North Carolina and Cooper Creek, Georgia were subjected to comprehensive hematological and serum chemistry studies. The majority of the results were similar among all populations. We attributed the few significant differences to confounding factors such as time of collection or local adaptation (Solis et al., 2007a). These authors noted that at least 50% of the *C. a. bishopi* had leeches attached, but only one of 33 tested positive for blood parasites. They used MS-222 in their protocol, which is known to mask parasitic load, but it is unknown if this may have effected their findings (Byram and Nickerson, 2012).

Leech parasitism may also contribute to the decline of *C. a. bishopi by* affecting their physiology and behavior (DuRant et al., 2015). We found leeches on most of perhaps 2,000 *C. a.*

bishopi surveyed in NFWR between 1968 and 1972 (Nickerson and Mays, 1973a). On 24 September 1972, we inspected 53 *C. a. bishopi* from the 4.6 km NFWR research section for leeches (Johnson and Klemm, 1977). Two individuals were leech-free and the range per individual was 0–48. We frequently found the leeches, currently *Placobdella cryptobranchii,* in clusters of 6–8 individuals and associated with cutaneous sores. Individual *C. a. alleganiensis* in Virginia infected with leeches have circulating leucocyte shifts characteristic of parasitic infections; immune responses were less robust in juveniles than in adults (Hopkins et al., 2016).

Factors Corresponding with Hellbender Population Decline: Deforestation, Development, and In-stream Habitat Changes

Deforestation in Ozark County is primarily removal of trees for non-forest purposes and typically for expected economic gain from activities such as agriculture (crops and pastures), logging for lumber and charcoal, ore mining, gravel mining, recreational areas, and exurban residential and business development (Quick, 2016). Deforestation and subsequent land cover and land use changes resulted in immediate and on-going changes to both terrestrial and aquatic environments, including increased erosion and runoff, increased temperature and CO_2, decreased humidity and dissolved O_2, changes in the hydrological cycle, and reduced soil cohesion (Moss, 2010).

The amount of deforestation in Jack's Fork and Piney River drainages north of our NFWR Research Section are well documented historically (see Jacobson and Primm, 1997; Miller and Wilkerson Jr., 2001). The eastern Ozark region encompassing the historically pine-dominated Current and Eleven Point River watersheds underwent substantial deforestation facilitated by railroad networks used for transporting timber (Anon., 2016). In 1880, The Missouri Lumber and Mining Company (MLMC) initially purchased 110,000 acres within the Current River basin, built a railroad to it, and established a lumber mill in Grandin near the Current River. The Grandin Mill soon became the largest lumber mill in the world consuming 70 acres of woodland per day and converting it to 220,000 to 250,000 board feet of wood per day (Palmer, 2010). Other large lumber mills were located near Birch Tree, Greenville, West Eminence, and Winona on the Jack's Fork and Current River basins (Palmer, 2010). The three MLMC companies operating in Shannon County reportedly cut 1.3 billion board feet of lumber between 1888 and 1903, and in 1910 nearly all of the pine had been cut and the Grandin Mill closed (Palmer, 2010). Surveys of contemporary *C.a. bishopi* populations in Current River drainages produced significantly fewer individuals than in Ozark County (Nickerson and Mays, 1973b; Briggler et al., 2007).

Forest harvesting in most of Ozark County differed greatly with that within the Current River drainage and other sites to the north and east. In the 1880s, harvest of most of Ozark County Shortleaf Pine (*Pinus echinata*), largely confined to the northeast one-twentieth portion of the county, was almost completed. Harvest of Black Walnut (*Juglands nigra*) along riparian habitat of larger tributaries was also completed in the 1880s. However, the oak forests had hardly been touched (Quick, 2016). The sites of selective harvest of pine trees in northeastern Ozark County are distant from our research site within the oak-dominated NFWR Watershed in southern Ozark County. The lack of railroads to facilitate timber transport is in stark contrast to Current River drainage forests to the east, so the NFWR Watershed was not historically subjected to such extensive deforestation (Miller and Wilkerson Jr., 2001). Lumber was transported to market using oxen teams initially and later with mules. This required many days to reach "transfer markets" such as Springfield, and then a month for a roundtrip to St. Louis (Quick, 2016). Much data similar to nearby counties are lacking for the NFWR drainage, but we assume some patterns observed in the drainages studied by Jacobson and Primm (1997) are similar. Initial surveys of the NFWR basin during 1968–1969 revealed a highly vegetated, forested riparian zone and adjacent forests, including stretches with pre-existing upland clearings for private residences and agricultural lands (see Nickerson and Mays, 1973a for NFWR plant diversity). Several deforestation events occurred up-steam and adjacent to the 4.6 km research section during 1968–2007 (Table 1).

During 1971–1972, a new canoe ranch operator cleared the riparian vegetation and expanded the removal of adjacent upland habitat from a large portion of the west side of the research section (Nickerson and Mays, 1973a, Fig. 2). Sand, silt, and small particulates were dispersed downstream for several hundred meters. In 1972, the MDC bought property along the east side of the research section and cleared the riparian and associated upland vegetation for establishment of a recreational facility that included parking, a primitive restroom, and a concrete boat ramp. The boat ramp emptied into the most important riffle (riffle 2–3) that contained adult Ozark Hellbenders (269 estimated) and >90% of known gilled larvae (Nickerson and Mays, 1973a,b; Peterson et al., 1983; Nickerson and Krysko, 2003; Nickerson et al., 2003). This development created a silted alcove adjacent to and downstream from the ramp, and increased distribution of small particulates along eastern margins (M. Nickerson, pers. obs.). During that period, another landowner expanded the cleared area within the central portion of the upland habitat located on the west side of the research section for agricultural fields, an airstrip, and a boat ramp (Fig. 2). Some of that clearing encompassed riparian habitat.

Substantial in-stream habitat changes in the 4.6 km research section came from Ozark County's construction of a major new bridge that replaced a low water bridge several hundred meters upstream from the beginning of the research section (M. Nickerson, pers. obs.). Conditions became so degraded that in May 1998 the Missouri Department of Conservation (MDC) investigated the excessive turbidity and sedimentation to consider what measures might alleviate some of the damage to the stream quality (Miller and Wilkerson, Jr 2001). Sedimentation and short-term disturbances in habitat or water quality are detrimental to aquatic animals by altering recruitment and modifying population dynamics (Pugh et al., 2016).

In-stream gravel mining was practiced historically in the Ozarks and the NFWR watershed. In-stream gravel mining, especially using poor mining practices, threatens water quality and impacts riparian and aquatic habitats and their biota through increased sedimentation and turbidity. In 1998, 24 permits were issued for gravel removal projects within the NFWR watershed, but by that date, no permits were being issued for the sections of NFWR deemed highest quality for trout and Ozark Hellbenders (Miller and Wilkerson Jr., 2001). Most *C. a. bishopi* larvae were found in NFWR gravel beds (Nickerson et al., 2003, Fig. 3).

In 2004, riparian deforestation included the state-owned public boat ramp, a parking area and camping facilities on the east bank, and a privately-owned campground on the west bank just upstream of riffle 2–3. They covered an estimated 9.9 and 0.6 ha, respectively (Pitt and Nickerson, 2012; Fig. 2). The canoe ranch established on the west side of the NFWR deforested ca. 0.86 ha, and an access area downstream owned by another canoe ranch ca. 2.2 ha. A private residence was surrounded by a large waterfront lawn approximately 3.0 ha in size. State-owned camping facilities and river access sites deforested 1.0 ha (Pitt and Nickerson, 2012).

Table 1. Extent of deforested land occurrence in 1969 and 2004 immediately adjacent to the 4.6 km research section in the North Fork of White River, Ozark County, Missouri.

Stations	1969	2004
0-3	0 m^2	99,300 m^2
16-17	0 m^2	88,300 m^2
46	0 m^2	22,100 m^2
48-50	1,000 m^2	9,900 m^2

We discovered substantial changes in the river substrate during surveys in 2000 and 2002 and intensive surveys in 2004–2007 (Nickerson et al., 2009; Pitt and Nickerson, 2012). Surveys of the stream bottom in riffle 2–3 revealed that interstitial spaces in the riffle were filled with sand and fine particulates, and that gravel depth had effectively decreased by 58% (Pitt and Nickerson, 2012). Approximately 1600 m downstream from the beginning of the research section, a deep trough with overhanging ledges along each side used as refugia for Ozark hellbenders in 1969–1980s, was filled and covered with sand and small calcareous particulates. This trough emptied into a former deep pool approximately 600 m downstream. That pool was almost completely filled with particulates by the early 2000s. Formerly, depths of this pool were 2.5–3 m, and housed the second largest concentration of NFWR Ozark Hellbenders known (Nickerson and Mays, 1973a). All known nest sites and potential nest sites identified during the early surveys were covered with these particulates (Nickerson and Tohulka, 1986; M. Nickerson, unpublished data). We found smaller troughs under overhanging ledges elsewhere within the research section. On two occasions, we found that many individual hellbenders congregated in the exposed centers of these troughs after emerging from under the ledges during the breeding season (Nickerson and Mays, 1973). In West Virginia streams, reintroduced and translocated *C. a. alleganiensis* (n = 29) had a 20% mortality rate caused by burial under gravel and sediment during flooding (Greathouse and Felton, 2015). Deposition of sediment on artificial hellbender nest boxes and their openings is also considered a problem (Mohammed, 2015).

Sedimentation and siltation have been posited as drivers of hellbender population declines due to filling and subsequent loss of refuge and nesting sites, smothering of eggs due to silt and sediment accumulation, and loss of interstitial spaces used by larvae and invertebrate prey (Nickerson et al., 2003; Briggler et al., 2007). Increased sedimentation is linked to riparian habitat deforestation in the Spring River of Arkansas, which supported large populations of *C. a. bishopi* in the past (Trauth et al., 1993). Sensitivity and elasticity analyses conducted by Unger et al., (2013) suggested that survival of eggs and larvae significantly influenced hellbender population dynamics. Documented shifts in population size structure towards larger hellbenders suggested recruitment has declined in Ozark Hellbender populations, including those in the NFWR (Wheeler et al., 2003). Larval detectability's relationships to survey methodology were not well understood at that time. During the 1980s and 1990s, larvae were still occasionally found within the NFWR despite low population levels (J. Briggler, MDC, pers. comm., Nickerson and Krysko, 2003; Pitt et al., 2016). It is unclear if the postulated lack of recruitment is related to survey methodology, actual reduction of populations or successful nesting sites, reproductive dysfunction, or a combination of factors. Increased sedimentation and siltation that filled interstitial spaces with small particulates could be a significant factor in hellbender decline because it removed known larval habitats that were heretofore considered secure from many potential predators.

Siltation and sedimentation also provided suitable substrate for establishment of emergent vegetation stands within the NFWR since 2004 (Tavano, 2008; Nickerson et al., 2009; Pitt and Nickerson, 2013). We observed establishment and spread of emergent vegetation and increased amounts of floating and submerged filamentous algal mats and growths in 2004–2007 (Tavano, 2008; Pitt and Nickerson, 2012, 2013, 2014). They are symptomatic of nutrient loading commonly associated with deforested upland and riparian habitats (Dodds, 2006). Documented total phosphorus and total nitrogen levels for NFWR in 1994–1997 and 2004 exceeded acceptable U.S. Environmental Protection Agency (EPA) levels for streams (Solis et al., 2007b). Vegetation may alter stream flow dynamics and initiate a positive feedback cycle by allowing further accumulation of sediment and subsequent spread of vegetation (Green, 2005). Furthermore, increases in primary productivity may alter water quality parameters such as dissolved oxygen levels (Caraco and Cole, 2002). Alterations to stream flow dynamics and dissolved oxygen levels impact aquatic vertebrate species, including hellbenders (Miranda and Hodges, 2000).

Coliform bacteria surveys in NFWR conducted in June-August 2007 indicated that *Escherichia coli* levels within the research section exceeded concentrations deemed safe for full human body contact during at least one sampling event (Missouri Department of Natural Resources [MDNR], 2005; Nickerson et al., 2009; Pitt and Nickerson, 2014). In contrast, only one sample from one site located upstream within the heavily forested MTNF had *E. coli* levels that exceeded concentrations deemed safe by the MDNR (Pitt and Nickerson 2014). Sources of *E. coli* were likely septic systems in streamside houses and businesses during the riparian and adjacent upland deforestation events.

Run-off following deforestation and development may also introduce chemical contaminants into the NFWR. Solis et al. (2007b) studied the occurrence of nine bioactive organic chemicals in two Ozark hellbender rivers, the NFWR and the Eleven Point River. Chemicals, including those with known estrogenic effects, were at much lower levels than those known to have reproductive or other biological effects in other amphibians (Solis et al., 2007b). NFWR Ozark Hellbenders had significantly greater levels of cobalt in their blood, a known agent that causes mortality, than *C. a. alleganiensis* and *C. a. bishopi* from other streams (Huang et al., 2010).

Exploitation

In addition to altering in-stream habitats, deforestation and subsequent development projects, including public access points along the NFWR, allowed for and encouraged easy human access to locations containing historically large hellbender populations. In 1980, major illegal harvesting of *C. a. bishopi* and turtles were discovered within the NFWR research section (Bartlett, 1988; Nickerson and Pitt, 2012). In one incident during the 1980 Labor Day weekend, members of the Nebraska Herpetological Society flew to the NFWR, landed at the nearby airstrip, and harvested 156 *C. a. bishopi* from the research section (Bartlett, 1988; Nickerson and Briggler, 2007). The MDC received documentation that a collector from Alabama removed more than 100 individuals between 1982 and 1984 that he shipped to Japan (Nickerson and Briggler, 2007). We documented harvesting of 558 Ozark hellbenders during 1969–1989 within or near the NFWR research section that included 272 removed for scientific and educational use (Nickerson and Briggler, 2007). Long-lived species are particularly vulnerable to collection pressures because their delayed sexual maturation does not allow for rapid population recovery following decline (Congdon et al., 1993). Collection of *Graptemys geographica* (Northern Map Turtles) from the NFWR research area resulted in a reduction of the population to approximately half of its original size (Nickerson and Pitt, 2012; Pitt and Nickerson, 2012). The turtle population did not recover until approximately three decades (estimated lifespan of *G. geographica*) after the last major collection event (Pitt and Nickerson, 2013). Declines due to collection have also been noted for a wide variety of reptile species (Gibbons et al., 2000). The intensity of collection coupled with *Cryptobranchus* life history traits (e.g., long life, delayed sexual maturation) suggest these collections contributed to the decline.

Increased Access and Recreational Use

Deforestation and subsequent development projects that included establishment and expansion of canoe ranches, camping facilities, lodging, and public access points along the river allowed for and encouraged recreational use throughout the NFWR, including in areas containing *C. a. bishopi* populations. Recreational users of the NFWR impact hellbender populations in a variety of ways. For example, we have observed people swimming and wading alter the stream substrate by moving rocks to build small dams to pool water for swimming areas near the public access points. In such instances, shelter rocks were moved into an area that is or becomes unsuitable for hellbenders (M. Nickerson, pers. obs.). These small dams disrupt water flow and promote accumulation of sediment in the more lentic habitat created.

Canoeing, kayaking, rafting, and floating on inflatable tubes are increasingly popular activities in the NFWR. In the late 1960s to 1971, canoes were uncommonly encountered on weekdays, except for small groups from a local camp. However, canoe observations increased from a mean of 5/weekday in 1980 to 21/weekday in 2004 (Pitt and Nickerson, 2012). Several canoe rental businesses use the research section daily during late spring through fall especially on weekends. In 2004, a single "canoe ranch" launched up to 140 canoes per day, and as many as 135 tubers traversed the river in a single day (Nickerson et al., 2009; Pitt and Nickerson, 2012). Although more recent estimates of recreational use have not been systematically quantified, the privately and state-owned facilities continue to be used heavily. Some of the canoe rental facilities are expanding (Fig. 2). Increases in recreational use of the NFWR is of concern because canoes, kayaks, rafts, and people floating on tubes may disrupt shelter rocks in riffles causing injuries to hellbenders (Fig. 4), especially during time periods when water levels are low.

CLIMATE CHANGE AND DEFORESTATION

Climate change is altering temperature and precipitation patterns that, in turn, impact freshwater ecosystems (Gates, 2008; Jiménez Cisneros et al., 2014). Consistent with climate change models, there were more cooling degree days in south-central Missouri during 2004–2007 than in 1969–1972, and warmer temperatures recorded in March during these years indicated an earlier onset of spring temperatures (Nickerson et al., 2009). Impacts of increasing temperatures may be exacerbated by deforestation because loss of riparian habitats eliminates thermal buffering of streams provided by trees (Brown and Krygier, 1970; Kaushal et al., 2010). Warmer water temperatures may directly and indirectly impact hellbenders and other cool-water species through sub-lethal effects associated with thermal stress (Nelson and Palmer, 2007) and alterations of water chemistry such as reduced levels of dissolved oxygen (Welsch, 1991).

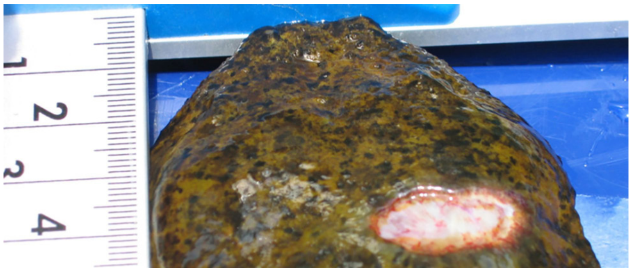

Figure 4. Injury to adult Ozark Hellbender (*Cryptobranchus alleganiensis bishopi*) attributed to a canoe hitting a shelter rock. This is the type of injury we occasionally observed after busy canoe days in the early 1970s when rocks were dislodged and the upstream rock surface had metal particulates. Photo credit: Amber L. Pitt.

Climate change that alters temperature and precipitation patterns has been linked to extreme hydrological events, such as flooding (Jiménez Cisneros et al., 2014). A review of NFWR flooding trends indicate that there were 11 days between 1 October 1944 and 9 October 2016 when mean stream daily discharge surpassed levels of 566 m^3/s (Fig. 5). Only one day (15 April 1945) and no days prior to 1985 for which data are available (1 October 1944 – December 1984) surpassed 566 m^3/s and 708 m^3/s mean daily discharge, respectively (Fig. 5). The other floods in which mean daily discharge levels exceeded 566 m^3/s occurred since February 1985, with two events in 1985, two in 1993, two in the 2000s, and four since 2010 (Fig. 5).

The effects of flooding on large aquatic salamander populations in non-controlled streams are understudied and difficult to evaluate, primarily because of the unpredictability of floods. Most knowledge of flooding effects on hellbenders is based on anecdotal observations (e.g., Humphries, 2005; Miller and Miller, 2005). One of the largest NFWR floods during the early years of data recording, prior to hellbender population declines, occurred in 1969 and reached a mean flow of 524 m^3/s. There was no evidence, based on subsequent population estimates, that the 1969 flood negatively affected NFWR Ozark Hellbender populations (Nickerson et al., 2007). In comparison, a May 2003 flood affecting the Middle Prong of Little River in the Great Smoky Mountains National Park

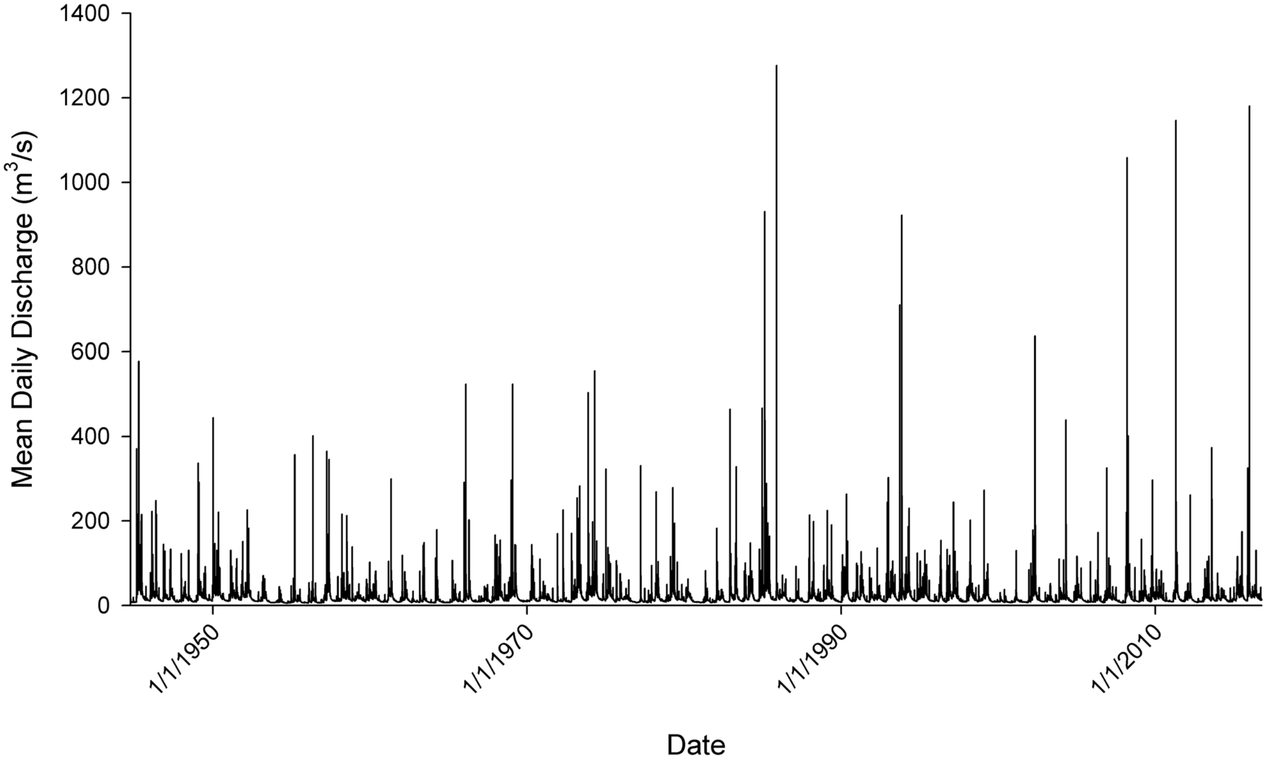

Figure 5. Mean daily discharge in cubic meters per second of North Fork of White River, Missouri, USA at USGS gauging station (07057500) downstream from the 4.6 km research section.

in Tennessee apparently eliminated most of the *C. a. alleganiensis* at least in the short term from the areas surveyed (Nickerson et al., 2007). Limited data indicated that floods may affect hellbenders both directly (e.g., flood-caused mortality) and indirectly (e.g., altering streambeds, thus reducing suitable habitat or prey abundance). The effects on hellbenders and their habitat by the more frequent, higher volume floods observed in recent decades in the NFWR warrants further monitoring and investigation.

Other Factors Impacting NFWR Hellbenders

Causes of the increased NFWR *C. a. bishopi* injuries and abnormalities are unknown. The chytrid fungus, *Batrachochytrium dendrobatidis*, a major factor in amphibian decline and extinctions (Wake and Verdenburg, 2008; Rödder et al., 2009), was in the NFWR population since at least 1969, with no known pathological outbreaks (Bodinof et al., 2011). A large study of microorganisms cultured from injured and repressed tissue regeneration sites in NFWR *C. a. bishopi* found known amphibian pathogens and many obligate pathogens associated with injuries and abnormalities, but no single pathological agent (Nickerson et al., 2011).

The increased percentage of the population with injuries and abnormalities, especially serious ones, correlates with the reintroduction of 40 (20 males and 20 females) River Otters (*Lontra canadensis*) and their associated microbial communities from Louisiana into the NFWR watershed on 5–6 March 1991 (MDC Otter Release file report, 1991). The reintroduced otters were not only potential vectors for non-native pathogens, but acted as predators and competitors for crayfish prey (Hecht et al. 2014, Fig. 6). This was one of the country's most successful carnivore introductions. The Missouri's otter population was estimated to be 3,000 in 1995 and projected to reach 18,000 by 2000 (Mowry et al., 2015). An otter can catch and quickly consume adult hellbenders (Hecht et al., 2014). Furbearers were responsible for 80% of

Figure 6. An adult River Otter (*Lontra canadensis*) feeding on an adult Eastern Hellbender (*Cryptobranchus alleganiensis alleganiensis*) in Little River, Tennessee, USA. Photo credit: Rick Vollbrecht.

the mortality of reintroduced and translocated *C. a. alleganiensis* (n = 29) in West Virginia streams (Greathouse and Felton, 2015). Otters were successfully reproducing in our NFWR research area by 2004 (Pitt and Nickerson, 2012).

Another potential source for pathogens comes from multiple fish hatcheries from which introduced Rainbow Trout (*Oncorhynchus mykiss*) and Brown Trout (*Salmo trutta*) are sourced. While it is unknown if injuries and abnormalities were caused by novel (e.g., introduced through otter or trout releases) or preexisting (e.g. *Batrachochytrium dendrobatidis*) pathogens, *C. a. bishopi* tissue regeneration may be repressed by infection and immunosuppression associated with environmental stressors (Scadding, 1977; Young et al., 1983; Johnson et al., 2006). Considering the current environmental state of NFWR habitat, immunosuppression as a result of environmental stressors (e.g., increases in river use coupled with microbial levels, solar radiation associated with reduced canopy cover, and changes in water chemistry parameters) may be contributing to the lack of tissue regeneration.

CONCLUSIONS

Forest removal that occurred in the NFWR corresponds with a cascade of effects that negatively affected *C. a. bishopi* populations. Clearing of riparian and adjacent upland forests exposed thin soil, limestone, dolomite, and sandstone. The lithological breakdown of these Ozark Soil components produced silt, sand, chert, and a massive amount of small calcareous particles that washed into the river, altering stream substrate. Siltation, sedimentation, and redistribution of gravel within the NFWR reduced suitable hellbender habitat. In-stream habitat was further impacted by record flooding events and increased run-off. Riparian and nearby upland vegetation deforestation, establishment of public and private camping and lodging facilities, and river access points led to greater recreational use of the NFWR and facilitated collection of hellbenders and other native species. The degraded state of the NFWR may be contributing to the high rates of abnormalities and injuries and the repressed tissue regeneration observed. Climate change may exacerbate the impacts of in-stream habitat degradation and contribute to immunosuppression associated with thermally induced changes to the environment.

Our long-term study of the NFWR hellbender population and habitat provides evidence of how deforestation and the subsequent land use alterations have caused myriad, and often unforeseen, cascading effects on native wildlife populations. Additionally, it allows elucidation of impacts that may not be apparent in the short-term, which is particularly important considering that population declines of long-lived species are difficult to detect in short-term studies (Wheeler et al., 2003). Although the impacts of deforestation on siltation, sedimentation, and run-off are well documented and relatively predictable, the potential effects of increasing river accessibility on aquatic wildlife populations is less clear but no less important given the exploitation rates of native herpetofauna (Gibbons et al., 2000) and the predictable slow population recovery of long-lived species (Congdon et al., 1993). Data available for the NFWR also provide insight into trends occurring throughout the *C. a. bishopi* range. All populations of *C. a. bishopi* have declined dramatically, leading to the 2011 listing of this species as a federally endangered species (USFWS, 2011, 2016). Many of the trends, especially those related to habitat degradation and disease vectors documented for the NFWR are consistent throughout Ozark Hellbender range (Briggler et al., 2007), although long-term data sets for most other streams are not available or missing important components.

The riparian and nearby upland deforestation and land use change and resultant within-stream habitat conditions correspond with a reduced carrying capacity for Ozark Hellbender populations in the NFWR compared to past decades. In recognition of the problems, the MDC created the North Fork Watershed Assessment and Inventory (Miller and Wilkerson Jr., 2001) to serve as a planning guide for restoring the NFWR and its riparian zones. Additionally, the MDC and Saint Louis Zoo implemented a wide variety of conservation actions targeting Ozark Hellbenders. We are optimistic that the combined efforts of the Mark Twain National Forest, Missouri Department of Conservation, St. Louis Zoo, landowners of the North Fork drainage, and the dedicated scientists and interested citizens will lead to the protection of the NFWR from further perturbations.

Management Implications

Review of how historical landscape alterations negatively affected a high profile, endangered aquatic species provides an impetus for restoring the ecological integrity of the habitat in order to recover affected populations. The MDC's North Fork Watershed Assessment and Inventory is the current planning guide for the state's efforts to restore the North Fork of the White River and its riparian zones. It is an example of how complex ecosystem restoration may be accomplished and demonstrates the benefits of stakeholder cooperation. The plan's primary goals include: 1) improve riparian and aquatic habitats; 2) improve surface and subsurface water quality; 3) maintain abundance, diversity, and distribution of aquatic biota; and 4) increase public awareness and promote wise use of aquatic resources. Success depends on forming partnerships with landowners and other stakeholders to develop management guidelines and recovery projects that are effective in the context of the NFWR environment. These cooperative efforts could provide long-term benefits for both endangered species and humans as ecosystem dynamics and services are restored. Successful restoration of the river and adjacent landscape will enhance the quality of recreational experiences and provide economic benefits for the region, in addition to aiding in endangered species recovery.

ACKNOWLEDGMENTS

We acknowledge the help of all of the collaborators, past and present, and the agencies that supported the research and conservation of hellbenders and habitats. Their names are included in the publications cited in this paper and elsewhere. Funding was provided by the St. Louis Zoo Wildcare Institute, Reptile and Amphibian Conservation Corp (RACC), Arkansas State University, Milwaukee Public Museum, Nunnemacher Research Fund, Miller Research Fund, Karl Schmidt Research Fund, Missouri Dept. of Conservation-Natural History, Max Allen's Zoological Gardens, Cryptobranchid Interest Group, and Jennifer Elwood Conservation Fund. We especially thank Deanna Olson whose thoughts and efforts were responsible for the "Salamanders: World Icons of Aquatic Biodiversity in Forests" symposium at the XXIV International Union of Forest Research Organizations World Congress where a portion of this contribution was presented. We also thank Stan Trauth, editor for this manuscript, and the reviewers for their constructive comments.

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