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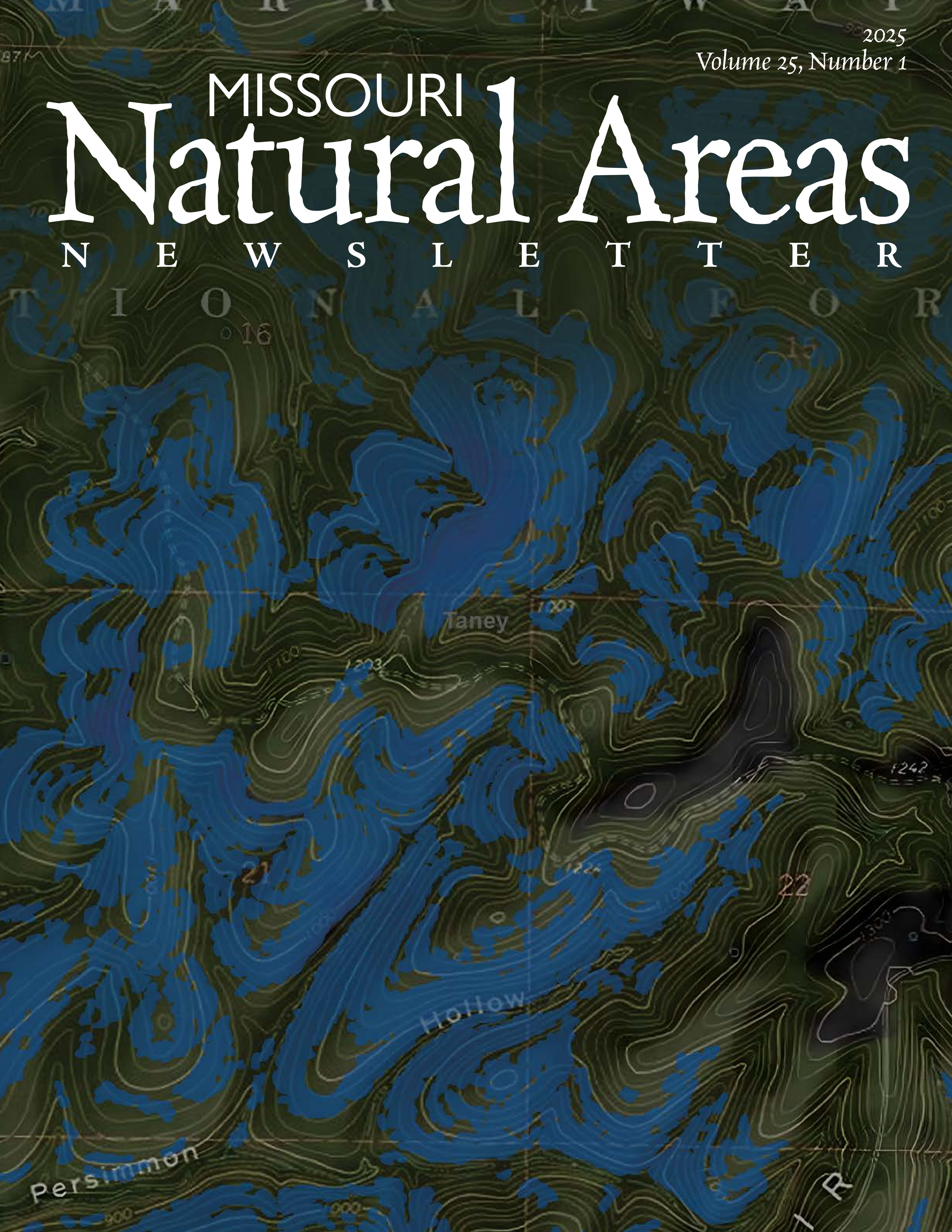
Volume 25, Number 1

MISSOURI Natural Areas NEWSLETTER



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NEWSLETTER

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"…identifying, designating, managing and restoring the best remaining examples of natural communities and geological sites encompassing the full spectrum of Missouri's natural heritage"

Editor's Note

Technology in Conservation

In 1942, Ralph Erickson, Louis Brenner and Joseph Wright pioneered the first effort to map glades in eastern Missouri using 1937 aerial photography as a method to map the extent of Fremont's leather flower (*Clematis fremontii*) occurrences. Their map resulted in approximately 3,500 glades transferred onto county road maps and provided a moderately accurate depiction of the patterns and distribution of glades in Jefferson and part of Franklin counties (Erickson, et al. 1942). Forty-one years later in 1983, ecologists and former Missouri Natural Areas Committee members Paul Nelson and Doug Ladd published *The Preliminary Report on the Identification, Distribution, and Classification of Missouri Glades* (Nelson and Ladd, 1983) once again using aerial photography to detect the presence of glades. They commissioned the service of Janet Hicks who completed a master's thesis study of the glades of Hercules Glades Wilderness in southwest Missouri (Hicks, 1981). Using 7.5′ quadrangle topographic maps provided by the United States Geological Survey she used a magnifying stereoscope to identify glades for portions of the Missouri Ozarks. This time-consuming process ended before completion and Nelson and Ladd estimated the number of glades per quadrangle based on field experience and her limited work.

Fast forward to 2009 and the widespread availability of ArcGIS, a geographic information system (GIS), which allowed Nelson and others to visualize, analyze and interpret spatial data to answer questions about relationships, patterns and trends of the presence of glades in Missouri. The Natural Glades shapefile was originally published by the Missouri Spatial Data Information System (MSDIS) in 2014 and updated with the revised geology map in 2018. In 2022, Nelson, Missouri Geological Survey's Larry Pierce and I published the report *Comprehensive Distribution and Characterization of Missouri's Glade-Producing Rock Formations* (Nelson, et al. 2022) which highlights the multi-year mapping process that resulted in over 97,000 mapped glades in Missouri. Technology and field verification for testing purposes made this map possible.

In this issue you can read on about how drone technology is helping in wildlife surveys for grassland birds and exotic species detection; a new and affordable technology that can also aid in determining, for example, deer populations to demonstrate the need for managed hunts. Biologists are also employing minute wildlife tracking devices to follow wildlife migration patterns. The theme of this issue dovetails well with the theme of the 2026 Missouri Natural Resources Conference to be held in February in Osage Beach, "Innovation Conservation." Mapping technology has brought on revolutionary changes in the National Wetland Inventory which you can read about from wetland specialist Frank Nelson with the Missouri Department of Conservation.

Conservation has come so far since the movement began in earnest in the 1930s. There are, of course, some challenges with technology like Autonomous Recording Devices (ARUs) to record bird calls that can develop an inventory of birds in a given area but oftentimes with incorrect detections. It is up to the specialists to help aid technology to work *with* us instead of replacing us. Technology is clearly here to stay and advance, and it is incumbent on the knowledgeable stewards of the land and wildlife to do the field truthing, the verification of models, so we may all work to make technology a tool to help conservation, not replace the brainpower of so many skilled ecologists.

— Allison J. Vaughn, editor

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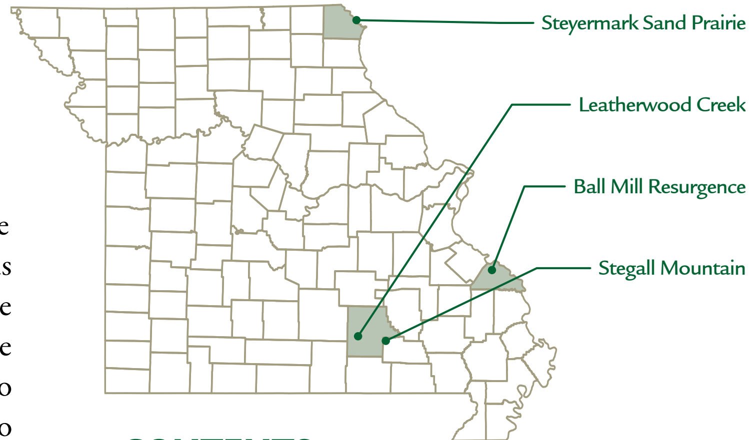
Nelson, P.W. Vaughn, A., Pierce, L., 2022. The comprehensive distribution and characterization of Missouri's glade-producing rock formations. Missouri Department of Natural Resources, Missouri Geological Survey. Special Publication No. SP-14p., 146 figs., 24 tbls., 1 app.

Cover page photo: A snapshot of some of the Jefferson City Dolomite glades (blue) in Hercules Glade Wilderness on the Mark Twain National Forest, the result of a mapping project of glades in Missouri made possible with ArcGIS technology. (See Nelson, P.W. Vaughn, A., Pierce, L., above**)**

NATURAL AREAS FEATURED IN THIS ISSUE



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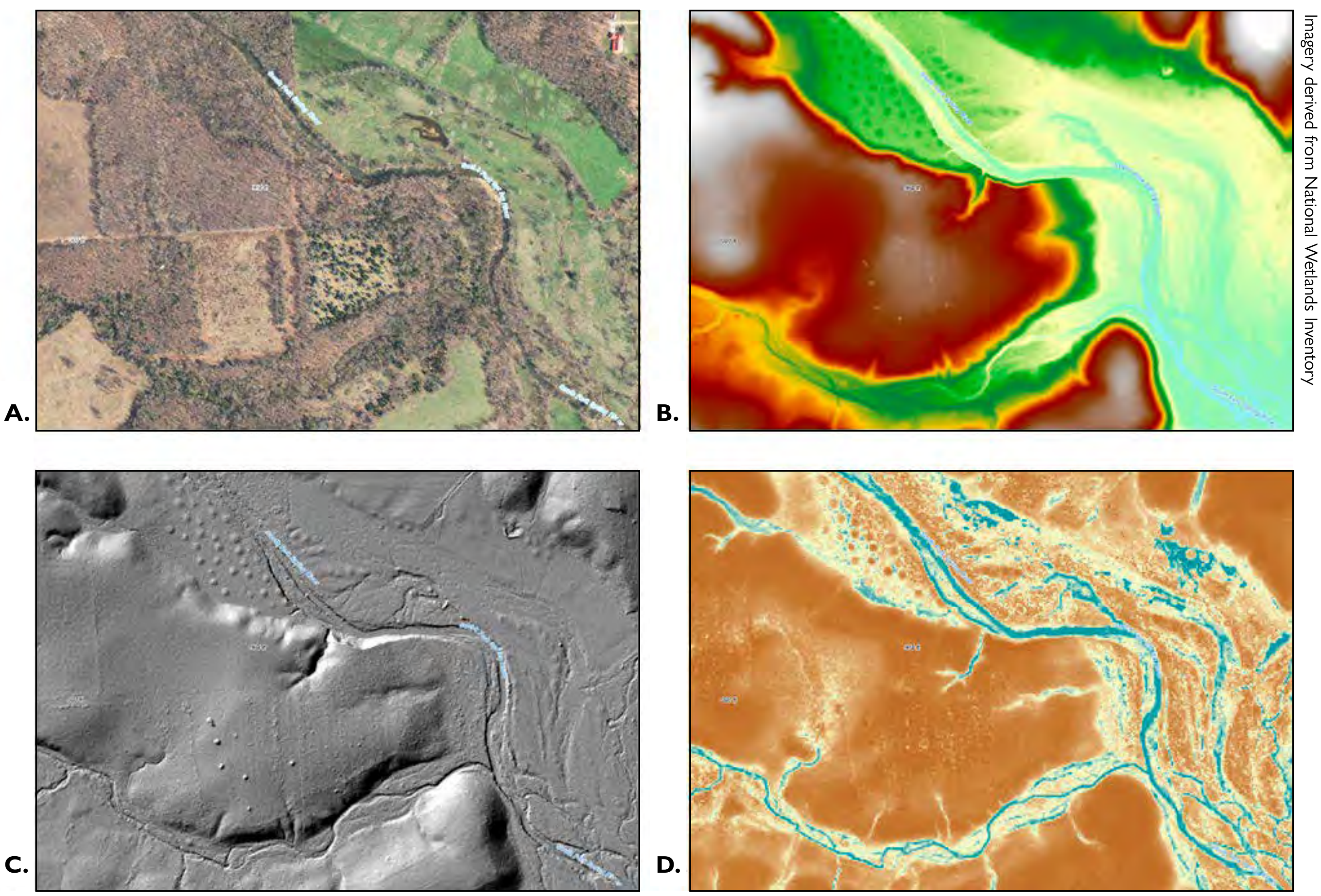
The ***Missouri Natural Areas Newsletter*** is an annual journal published by the Missouri Natural Areas Committee, whose mission is identifying, designating, managing and restoring the best remaining examples of natural communities and geological sites encompassing the full spectrum of Missouri's natural heritage. The Missouri Natural Areas Committee consists of the Missouri Department of Natural Resources, the Missouri Department of Conservation, the U.S. Forest Service, the U.S. Fish and Wildlife Service, the National Park Service and the Nature Conservancy.

Putting Missouri Wetlands on the Map, Literally

By Frank Nelson

2025 marked the fiftieth anniversary of the National Wetlands Inventory. Often referred to as NWI for short, this is *THE* geospatial wetland dataset for the United States. Although it is managed by the U.S. Fish and Wildlife Service, 165 different contributors helped build this dataset over the past half century. Back in the day, the creation process involved tediously hand-drawing wetland boundaries on mylar sheets that were overlaid on black and white aerial imagery. Fast-forward to today, and the process is largely digital with GIS technicians using mapping software and heads-up displays to run semi-automated computer processes, which analyze imagery, lidar derived topography, and other ancillary datasets to inform the position and type of wetlands mapped (Figure 1). Manual checks, ground-truthing, and interpretation are still necessary to ensure that the final GIS layer meets the same standards across the U.S. When comparing old NWI to newer data, the noticeable difference is accuracy and resolution of capturing a greater extent and wide range of different wetland types.

Figure 1. Multiple geospatial layers are used in the current process to develop the National Wetlands Inventory layer. **A.** is leaf-off imagery, **B.** is an elevation gradient from lidar, **C.** is a hillshade showing relief from lidar, **D.** is another lidar derivative estimating potential wetness based upon the curvature of the land.



Wetlands Defined

But before I get too far ahead of myself, you might be wondering, "What exactly is a wetland?" and "Why should I care if these are mapped?" As the name subtly suggests, wetlands are dynamic and can be wet or dry depending upon when and where you visit one. The legal definition requires the following three parameters:

- Hydrophytic plants, which are species that have adapted water tolerance strategies to handle soil conditions without available oxygen.
- Hydric soils, which are soils that have specific textures, characteristics, and colors because they developed during saturated or flooded conditions.
- Hydrology, which refers to the periods of time in which the soils are saturated or when ponding of water occurs through the growing season to influence the plant and soil characteristics.

Often, we can get hung up on a specific parameter, but from an ecological perspective, the emphasis is the interactions and processes that occur among the water, land, and life over time. These relationships inherently shape the various wetland types, health, and benefits.

Western Perspectives

Within the natural resource world, we often recognize the benefits that wetlands provide fish and wildlife for food and cover. However, the words and phrases used in the Western world often have a dark undercurrent or unpleasant connotation that these areas are meant to be avoided because of possible threats of disease, lawlessness, or tough conditions to traverse. For example, getting *"swamped"* is not typically considered a good thing. In the early 1900's the morally right thing to do with *"unusable land"* was to *"reclaim"* it, thus the wide accepted public policy of wetland conversion to agriculture. It reflects a command-and-control approach that also influenced the modification and literal streamlining of our *"wild"* river systems to reign in and reduce the natural variability of these dynamic aquatic systems. Even today, the phrase, *"drain the swamp"* is a call to remove political corruption. If we do vary our words to describe distinctive wetlands, they are focused on a static physical state, such as the dominant plant community. For example, swamps have trees and conjure up the picture of the gently sloping cypress and tupelo buttresses. Marshes are primarily herbaceous and invoke a vision of water and cattail (Figure 2). Water chemistry is another linguistic distinction highlighting which wetlands contain saline, brackish, or fresh water.

Figure 2. The words we use often describe a physical characteristic of a wetland. Swamps typically depict lowland forests with cypress and tupelo, whereas a marsh is a wetland dominated with herbaceous plants like cattail.

Photos by Jim Rathert

Eastern Perspectives

In comparison, if you look at the words used in Asia, where a long history of aquaculture exists and continues to this day, there are differences in the lexicon surrounding wetlands. The linguistic nuances are more focused on the functional and relational properties of managed wetlands and associated infrastructure of ditches and berms. Although China is the best know example of wetland aquaculture, archeology keeps uncovering an increasing number of examples across the globe that include North, South, and Central America, Australia, and Pacific Islands. These findings show a wide range of ancient people have historically worked with their landscapes and developed agro-ecosystems that were maintained for centuries, if not several thousands of years. These practices were likely sustained by the knowledge and value that was passed on through their language.

North American Indigenous Perspectives

Rather than a utilitarian point of view, which is often reflected in Western thinking, many Indigenous cultures do not separate knowledge and spirituality. We can see this in a couple different examples of words associated with water and wetlands among different North American Indigenous Tribes. Various tribes have their own language, traditions, and values that reflect their specific relationship with the land and species found in their local geography. On the east coast for example, the Pennacook-Abenaki language combines the root words *"Nebi"* for "water" and *"Nebiz8n"* for "medicine" to form the word *"Nebizonkik8n"* which translates to "Medicine Water Garden", highlighting this specific wetland type is an important source for medicinal plants. In the Great Lakes region, certain wetlands are central to the Ojibwe migration prophecy, which instructed them to move to the place where "food grows on the water." This phrase in Ojibwe, is "Manoomin" and stands for the wild rice lakes in the region, which are not just a food source but also sacred places. One final example involving the Lakota of the Great Plains has to do with the relationship with water, which can be scarce in the prairies. Water and the places from which it originates are held in reverence as a sacred entity. The phrase, *"Mni wičhóni"*, meaning "Water is life" conveys this weight and respect. From these perspectives the interconnected values and traditions are embedded in the reverent meaning within the languages and contribute to the protection and reinforced stewardship within their societies.

Wetland Status in the US

All this is to say, how we think about the world and the words we use make a difference and I find it interesting to compare and contrast these different societal values of wetlands to provide context on the past that has led us to the current wetland status of Missouri and the U.S at large. Since the 1780's the U.S. has lost 50% of its historic area of wetlands, and even more so in Missouri. With the narrow scale of floodplains, modification is feasible and over time technology has continually advanced to efficiently and continually enhance the diversion and drainage of water through the low-lying wet spots. By the 1980's only 13% of Missouri's historic extent of wetlands remained. If two hundred years of wetland conversion weren't enough, recent studies show that since 2009 the rate of wetland loss in the US has increased by 50% and the degraded health of existing wetlands are compounded by physical alterations, extreme weather events, increased nutrients, and expansion of non-native species.

With a diminished number of remaining wetlands scattered across our floodplains, we have begun to realize what we've lost. Without them we do not experience the same degree of multiple benefits that they provide. We have seen native flora and fauna suffer, as well as increased societal costs from not having as many wetlands around. Part of this is our lack of recognizing how different wetlands contribute various services based upon their landscape position, water source, and interactions with their surroundings. Unfortunately, recent Supreme Court rulings have focused on a narrow definition of what is covered by Waters of


Photo by Frank Nelson

Figure 3. The deep and organic-rich soil found in karst fens has accumulated over hundreds if not several thousand years because of the constantly saturated conditions. These soils act as a sponge, both holding onto water as well as slowly releasing it.

the U.S. rather than acknowledging the importance of ecological dynamics and interaction of the surrounding land and water. This has increased vulnerability and lack of protection for much of Missouri's remaining wetlands, which rely on federal regulations because of the lack of any state statutes.

Varied Wetland Services and Benefits

When present, wetlands can provide regulatory services, such as buffering the severity of fires and climate variability. If you need examples, look at the refugia beaver complexes provide amidst raging wildfires. Areas with greater green and blue spaces reduce and minimize the impact of heat domes in urban settings. Not only do wetlands allow for extreme rain events to slow down and spread out, but during droughts wetlands can sustain groundwater tables and stream flows by slowly releasing the water stored in the tight, and sometimes, organic soils (Figure 3). Supporting services include nutrient cycling, biodiversity, carbon cycling, and primary productivity. Sometimes these functions are visible by simply taking a closer look or knowing how to quantify these services through closer monitoring. For example, wetlands are globally the most productive ecosystem and sequester the most carbon per square foot. When it comes to biodiversity in Missouri alone, there are over 200 Species of Conservation Concern associated with wetlands. A similar abundance of species richness is also reflected in the microbiome of wetland soils when peering under the microscope or scanning a DNA array. We also depend on wetlands for provision, in the form of different types of food, fiber, forage, fuel, and clean water that come from these valuable habitats. Finally, there are cultural benefits. Most of us know about recreational opportunities and educational benefits, but more and more research is also underscoring the mental benefits that takes place when spending time in locations that are aesthetically pleasing or have spiritual significance.

Photo by David Stonner

Figure 4. Wetland restoration has occurred on flood-prone farm ground that has been voluntarily enrolled in the Wetland Restoration Easement (WRE) program. This example is an easement near Pershing State Park and Fountain Grove Conservation Area.

A Landscape of Unknowns

In essence, we cannot value what we do not know and unfortunately, many of us today do not have a direct connection or awareness of these spaces. It is "out there", even if we don't know where "there" is. Additionally, we cannot save what hasn't been measured. It's been nearly 30 years since wetlands were mapped according to NWI standards. Looking at the old wetland boundaries, some wetlands have been converted to corn and soybeans. In other locations, urban development has filled in the low spots and covered these locations with asphalt and concrete as another example of eating away at the old 13% historic extent estimate. National studies have shown that there has been an increase in the surface area of ponds, which is also likely the case here in Missouri, gauging by my roadside observations through urban and rural settings. Historic floods have provided an opportunity to set back levees and create complexes of engineered wetlands on public land. Nested within other flood-prone locations, the voluntary enrollment of Wetland Restoration Easements (WRE) has been a bright example of a government program facilitated by the Natural Resource Conservation Service (NRCS) and the Missouri Department of Conservation (MDC) since the mid 1990's (Figure 4). Currently, 166,729 acres of WRE have experienced restoration work, allowing water to slow down, spread, and stay a little longer on the landscape as a means to put back a part of what was lost.

With some wetland acres decreasing and other acres increasing over time, we don't have a good frame of reference of what exists across Missouri today. It is hard to prioritize what isn't measured and so as NWI celebrates its golden anniversary, we've begun to invest in updating Missouri's data. As alluded to earlier, the distribution and health of Missouri's wetlands are interconnected with the health of the adjacent rivers and streams. The spatial data of our river networks was equally dated, if not older in places, than our wetland data and in need of attention.

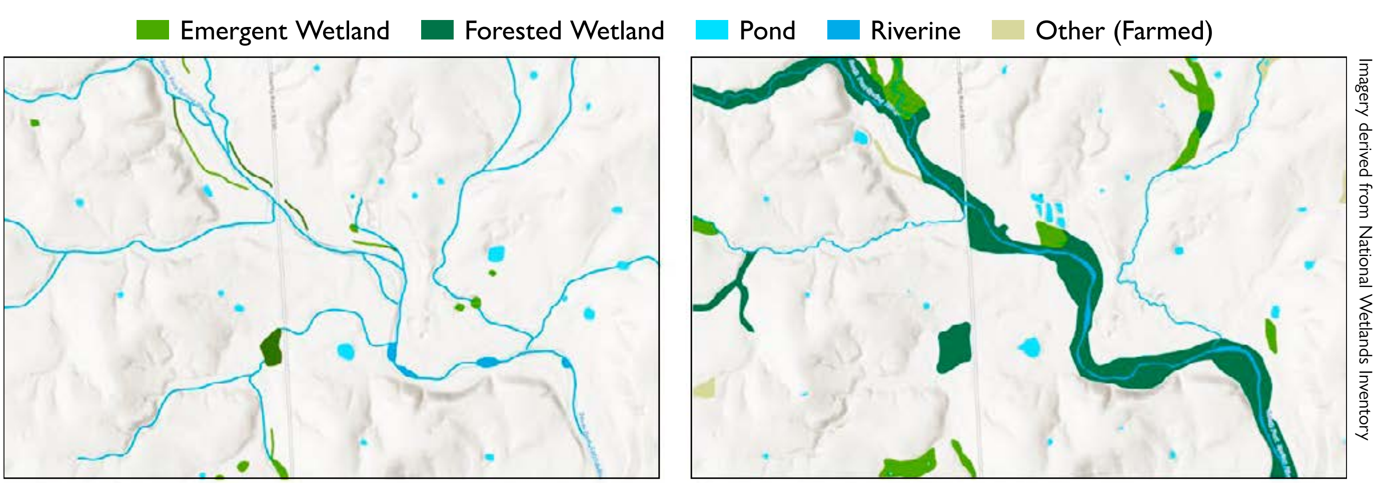
Mapping our Streams and Open Water

In the past 5 years MDC and its partners have been using recent, high resolution topography data to incrementally develop elevation derived hydrography (EDH) across watersheds as a part of the U.S. Geological Survey (USGS) 3D Hydrography Program. Within the year, approximately half of the state will have been updated with better resolution stream and water body data. This hydrography focused effort can be applied across disciplines in both the public and private sector by improving flood forecasting, enhancing water resource management, informing infrastructure planning, and more. With the boundaries of the streams identified, there are also efficiencies in mapping the adjacent floodplain and identifying existing wetlands by not having to double-handle the watershed topography.

First Look at New Wetland Mapping Efforts

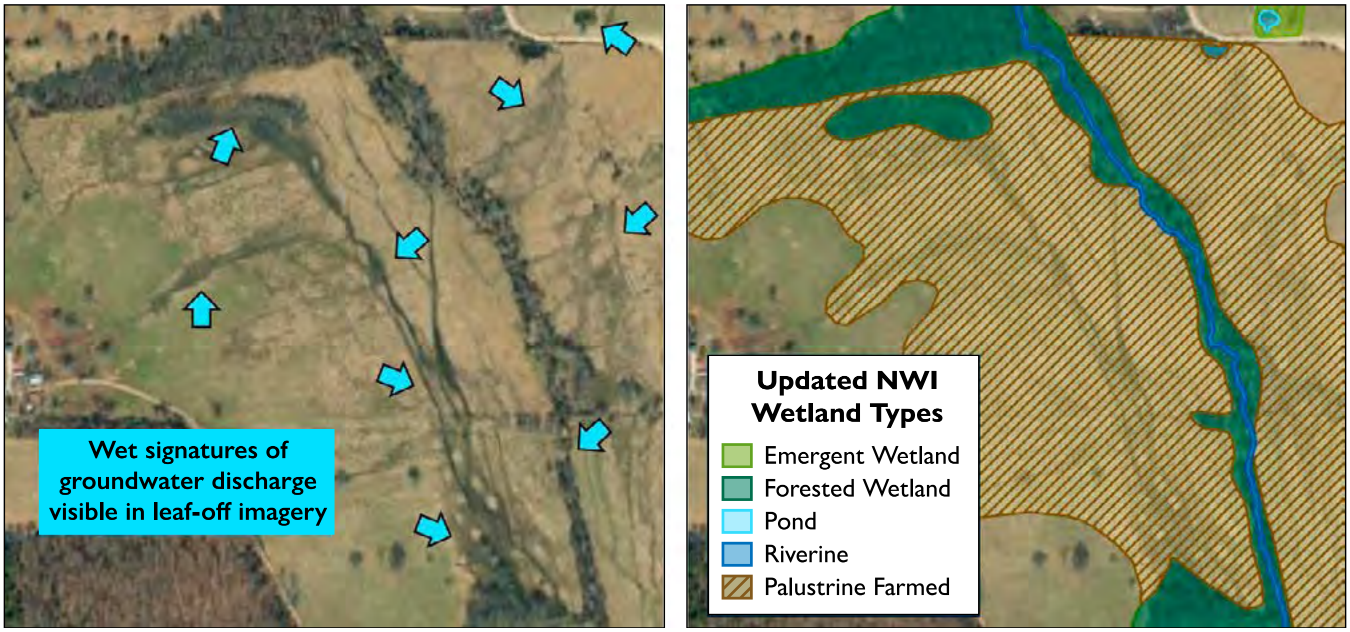
Last year, our NWI update work began in the Spring and Eleven Point watersheds in south central Missouri. This part of the state and these mid-sized rivers are not known as wetland meccas by any means. They are more characterized by rolling hills dotted by cattle pastures, blocks of forest, and fishable streams. The old NWI data looked like a series of blue ribbons as the habitat along the streams were classified as Riverine. Across the hills ponds dot the landscape and are coded as Palustrine open water features. If you look close enough within the floodplain, scattered around there are small, fragmented features coded as Palustrine emergent wetlands. When we look at the updated NWI we see some differences. Because of the enhanced resolution of imagery and topography, what was once all coded as Riverine, the new classification splits out the adjacent Palustrine Forest and Emergent wetlands next to the Riverine habitat within the stream channel (Figure 5). Across the hills, what was once assumed has been confirmed, there has been and continues to be an increase in the number of ponds built across the hills. Another exciting feature of the data is in the areas of small, scattered wetland fragments. Here again, the resolution of the imagery combined with analysis of the landform curvature has led to a better delineation of wetland boundaries. Granted, this is just a snapshot in time, and wetted areas fluctuate within and across years; however, a more complete compilation of wetlands, greater than a half-acre in size, have been mapped in these two watersheds. While smaller wetlands will still slip through the cracks, this new map is a drastic improvement and exciting promise for the rest of the state.

Figure 5. Contrasting the old NWI with the updated version shows that the use of better resolution imagery and topography has greatly improved the mapping extent of emergent and forested wetlands that run adjacent to riverine wetlands adjacent to Missouri's rivers and streams.



Old National Wetlands Inventory

Updated National Wetlands Inventory



Imagery derived from National Wetlands Inventory

Figure 6. There is a significant amount of acreage in the Spring and Eleven Point watersheds that are grazed or hayed that are still seasonally wet, which is visible in leaf off imagery. The updated NWI captures these locations as palustrine farmed wetlands, illustrating a segment of wetland conditions that has previously been overlooked in this region.

Major Wetland Types

The Spring and Eleven Point watersheds cover roughly one million acres, with 3% of the landscape, (~30,200 acres) mapped as one wetland type or another. Twenty-six percent of the wetlands mapped (totally ~7,820 acres) are classified as Riverine wetlands which include the habitats within and immediately adjacent to flowing water. Another chunk of wetland habitat making 19% of the mapped wetlands (5,740 acres) were coded as Forested/Shrub wetlands because of the woody structure present. Although ponds accounted for over 70% of the number of wetland polygons, the size of these small open water bodies added up to 16% (~4,850) of the total wetland acreage. You may have noticed, Emergent wetlands, the most commonly associated wetland type, has not popped up on the list yet. When you think of the Ozark landscape where the Spring and Eleven Point Rivers flow, the idea of emergent wetlands isn't the first thing to come to mind for this part of the state. That's because wetlands with herbaceous plants, like forbs, grasses, sedges, and cattail are in fact proportionately less common and only account for 12% (~3,630) of wetland acres.

If you've been keeping track of percentages, you may have noticed the tally hasn't added up to 100% yet is currently hanging at 73%. Another noticeable wetland footprint is locations that have been modified by ditches and diversions and are either grazed by livestock or hayed. Despite the alterations and current land use, these locations still have wet signatures present in the imagery. These locations are likely fed by seasonal groundwater discharge, which is commonplace in this karst landscape. Although the wetlands are altered and likely drier than they would be naturally, these wetlands are classified as Palustrine farmed, making up a surprising 26% of mapped wetlands, (~7,900 acres).

Previously Unconsidered Opportunities

These Palustrine farmed wetlands weren't on anyone's radar, even though these habitats wax and wane with wetness over time. While the physical and floral conditions of these wetlands are likely degraded, they represent an opportunity for new synergies with landowners to voluntarily improve conditions and our relationship with land and water in the Spring and Eleven Point watersheds (Figure 6). One consideration would be to temporarily fence cattle out and stockpile the grass until conditions dry out late in summer or early fall, which is what some landowners might already be doing within these soggy spots. On the other end of the spectrum, full-blown hydrologic restorations might be considered by plugging ditches and rerouting diversions to rehabilitate the footprint and extend the duration of wetted conditions. These are just two possibilities across a gradient of strategies. It is too early to tell what other options could be considered and who might be interested. Just knowing that these wetlands exist is an important discovery from, and a bright spot in our early NWI updating efforts that could potentially open up new doors and conversations centered around conservation.

Small Successes

The karst geology of the region contributes to 183 known springs that have been mapped by Missouri Department of Natural Resources (MDNR). Many smaller unmapped springs exist, as do seepy locations where groundwater seasonally or continuously saturates the soils. Traditionally, wetlands that aren't ponded but have soggy soils, are hard to map and a paltry five acres of this wetland type were accounted for in the 1980's iteration. Today, that number has grown to 1,470 acres, which is still only a small amount (4% of the total wetlands in the region) but helps identify locations where stream base flows may be gaining water and where different species may be found due to the distinct water chemistry. Here too is another small victory where knowing is half the battle. Checking on the quality and potential needs to manage or protect these unique areas will be next steps to follow up.

Surveying Extent of Ecological Engineers

Another aspect of wetland distribution that we know little about is the current distribution of beavers in Missouri (Figure 7). Yes, at a local level we know when beavers are causing problems. But at a statewide level, we don't know where these ecosystem engineers have worked under the radar and aren't causing problems. Part of this beaver blind spot is due to our complicated history. Like wetlands, beavers were once more abundant in Missouri and were thought to be extirpated from the state at one point in time. Continued trapping and slow population growth has shrouded the current population status. However, in certain streams and watersheds, one can occasionally stumble upon the presence of a beaver dam holding back water and creating a shallow pond upstream of

Figure 7. Additional attributes can be linked to wetlands, highlighting different forms of modification. The polygons in the image above were given a "beaver" modifier because of the visible signatures in the leaf-off imagery. The beaver activity was confirmed during a ground-truthing site visit.

Photo by Frank Nelson

Imagery derived from National Wetlands Inventory

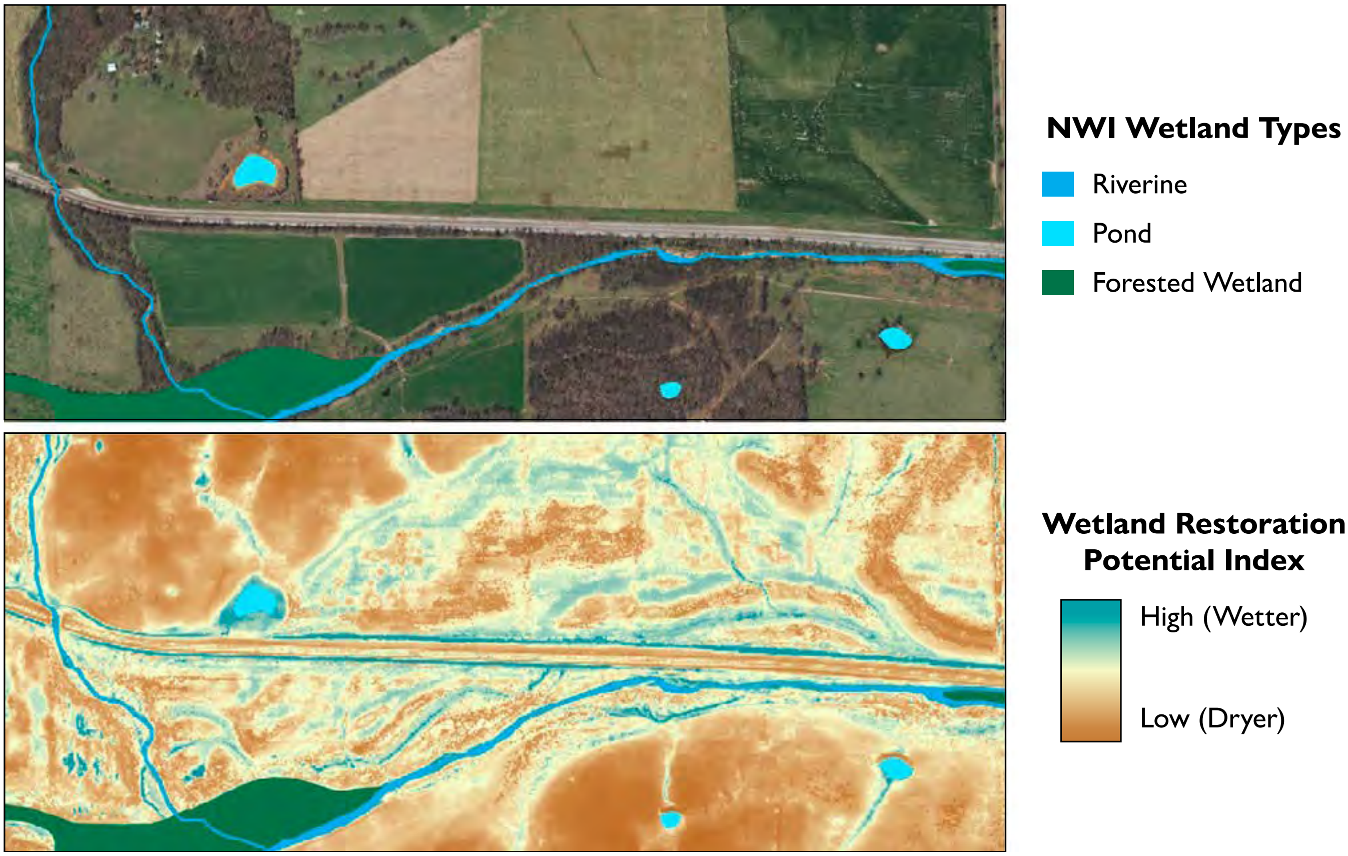


Figure 8. The top image shows leaf-off imagery and the updated NWI polygons. The bottom image shows another layer viewing the Wetland Restoration Potential Index which takes into account the curvature of the landscape at multiple scales with "wetter" locations being on the blue end of the spectrum and "dryer" locations being on the brown end of the spectrum.

these structures. Luckily, from the air these features (a linear obstruction to flow adjacent to an irregular ponded shape) are visible in imagery and provide a distinct signature that can be mapped and included in the wetland classification. We were able to see this proof in concept in the Spring and Eleven Point watersheds. With much of the land in private ownership and used for grazing, the numbers of beaver complexes amounted to a handful. However, the distinct shapes were there, and we are confident to be able to map more beaver complexes in places where they are more abundant.

Additional Purposeful Puzzle Pieces

Knowing where wetlands currently exist is crucial in keeping what we have. But this is just one piece of the puzzle. Looking for locations to restore or rehabilitate what was lost is another prerequisite piece to handle weather extremes and build back some of the resiliency that's been degraded and diminished over time. This need isn't restricted to Missouri and has been addressed by others using the same datasets employed to map current wetlands.

Proximity to existing streams and wetlands is a good place to start. Incorporating the slope of the land to find pockets prone to ponding is another landscape filter that can be applied. Looking for wet soil signatures is another clue to locate wetland restoration potential. As part of our effort to update NWI, we are aggregating these considerations and producing a layer that performs as another landscape lens to show an index of wetland restoration potential. It isn't absolute, "Yes, this could be a wetland" or "No, this will always be dry as a bone," but highlights features and locales across a gradient that could be given a closer look. Abandoned channels in old fields and depressional areas crossed by roads are the kinds of spots that this new layer highlights (Figure 8). From the ground the right combination of characteristics might exist, but only be visible during heavy rains, extreme flood events, or just a short period of time in winter or spring. However, by merging these factors into a new index, scientists and floodplain managers, and engineers can have another tool as a companion GIS layer to compare and plan with the updated NWI. In addition to what "is" this will provide a better vision of "what could be," which is currently obstructed from view.

Putting Wetlands on the Map

Wetlands are powerful places. Depending upon our varied perspectives, we have described and called these places different things, which ultimately reflected our values. Unfortunately, sometimes it takes losing something to realize its underlying importance. Wetlands are imperiled and have been off the radar for many Missourians. Yes, there have been some bright spots as the conservation mission has taken strides to retain and restore aspects of our floodplains and these critical habitats, but more must be done. Over the next few years, incremental progress across Missouri's watersheds will revitalize the utility of NWI, extending its applications as a critical GIS base layer for the next 50 years—an essential informative tool for both the public and private sectors to work ***with*** the landscape and all its nuances.

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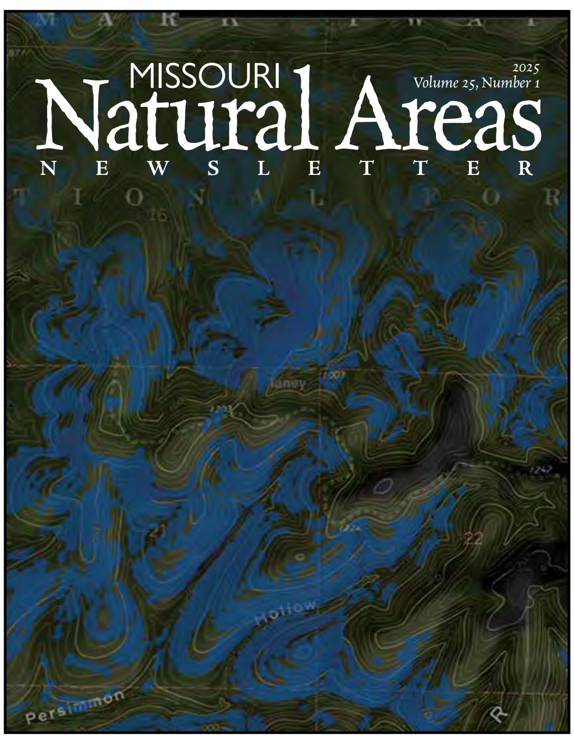

Missouri Natural Areas Newsletter Mailing List

To receive notification when new issues of the *Missouri Natural Areas Newsletter* are posted, e-mail Michael.Leahy@mdc.mo.gov.

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Photo by Dan Marschalek

Figure 1. One of several frosted dromo tiger beetles located on a roadside outside of Knob Noster State Park

Technology on a Small Scale for Insect Research: A Case Study of the Frosted Dromo Tiger Beetle (*Dromochorus pruinia*)

By Daniel Marschalek

Many conservation efforts aim to protect biodiversity and ecosystem functioning (United Nations 2015, Barbosa et al. 2019). Considering that over half of the described species on Earth are insects (Wilson 1987), with an estimated 5–30 million species worldwide (May 1988, Gaston 1991), insects should be a focal point because of their species richness and integral role in the environment. For example, insects pollinate most plant species (Ollerton et al. 2011), can contribute more to decomposition than vertebrate scavengers (Ray et al. 2014), and are an important food source for other animal groups such as birds (Kobal et al. 1998). Because of these functions, other trophic groups and levels are dependent on insects.

However, insect conservation is challenged with inherent characteristics of insects (Cardoso et al. 2011). Often, most insects are not known to the public and policymakers, and research is often underfunded. Currently, most insect species are undescribed, and for those that are described, we know little about their distribution, abundance, and sensitivity to habitat changes. These challenges to the conservation of insects means that we (scientists collectively) know and track only a very small proportion of insects. Consequently, data to demonstrate a need for conservation or to inform effective and efficient management are often lacking. However, progress is being made as we are developing a better understanding of many insects, in part due to advances in technology.

Figure 2. Dorsal view of a frosted dromo tiger beetle walking through sparse vegetation associated with red clay soils.

The frosted dromo tiger beetle *(Dromochorus pruinia)* is one insect in Missouri that would benefit from conservation efforts so that it is not lost from the state (Figure 2). While this species is found across much of Kansas, Oklahoma, and Texas, the only known Missouri location is Knob Noster State Park (Johnson Co.). According to a 2007 report written by Christopher Brown and Ted MacRae, only six specimens existed at that time, all collected in 1975 about 10 miles west of Warrensburg, Missouri along Highway DD (Brown and MacRae 2007). More on "10 miles west" later. They also note that a seventh specimen exists, but it appears to have been mislabeled. Brown and MacRae set out to rediscover the species in Missouri in 2005, then better understand its distribution in Missouri in 2006.

The tiger beetle was confirmed to still be in the state in 2005, with beetles observed along Highway DD in Knob Noster State Park. However, this is 10 miles **east** of Warrensburg rather than west as the label suggests. Again, another error in data recording. More extensive surveys occurred in 2006 to better understand the distribution of this species, with Brown and MacRae using visual surveys and pitfall traps. These surveys were focused at Knob Noster State Park, as well as a few locations in and around Johnson County. All of the frosted dromo tiger beetles that were either observed or trapped were found in areas with sparse vegetation and red clay soil along a 2.5-mile stretch of Highway DD within the state park (Figure 3).

Figure 3. A roadside along Highway DD where several frosted dromo tiger beetles have been observed.

More recently, I have made several visits to Knob Noster State Park, focusing on areas with sparse vegetation and red clay soils in hopes of learning more about their adult activity period (daily and annually), population sizes, and habitat use. A better understanding of this tiger beetle's habitat use should ensure that management can at least maintain its distribution and population sizes, if not enhance them (Figure 4).

Some of those inherent characteristics that pose challenges for insect conservation also apply to the frosted dromo tiger beetle. Few are aware of this species in Missouri, and it is unclear if we fully understand its distribution in Missouri. Population sizes are unknown, which is often a prerequisite to understanding how a species responds to change. The small body size (less than one inch) and short adult activity period (about one month) provide challenges to addressing these questions. What we know so far is that the adults are active from late June to mid-July, in sparsely vegetated areas with red clay soil, and most active during low light conditions (dusk). Several frosted dromo tiger beetle individuals have been consistently observed over the years within a 50 meter stretch of roadside, north of Hwy DD (Figure 5).

In 2018, the highest count during a survey was 11 individuals in one evening. In 2025, the highest count was only three individuals. There are other areas of the park that possess a similar substrate and habitat and may be searched. One sunny mid-morning in July did not reveal any in a more suitable area not located on a mowed roadside, however, future research may include this area.

Developments in technology, specifically smaller and more precise devices, provide an opportunity to learn more about this tiger beetle (as well as other small animals) and inform management decisions. For decades, wildlife biologists have been able to use radio telemetry and Global Positioning Systems (GPS) trackers to track individual animals. These require attaching a device onto the individual, which would be much too large and heavy for insects. Harmonic radar does not require such large devices and is starting to

Figure 4. The frosted dromo tiger beetle in Missouri has only been observed on open red clay soils with sparse vegetation.

Figure 5. Two adult frosted dromo tiger beetles in mating position.

Photo by Kristie Nelson, Missouri Department of Natural Resources

Figure 6. This tiger beetle has a harmonic radar tag attached to its pronotum (between the head and elytra). The glue and diode are evident by the shiny spot, but the tag wires are so thin that they are not clearly visible.

be used to track insect movements. In 2025, I started exploring its use to track the frosted dromo tiger beetle at Knob Noster State Park. One major difference between harmonic radar and other technologies is that the others require a larger device attached to the animal because it generates and sends a signal. On the other hand, harmonic radar only requires a small tag on the animal because the tag is reflecting a signal from a hand-held unit, back to the unit. This greatly reduces the size of the tag.

Tags are composed of two very thin and flexible wires extending in opposite directions from a central diode. The flexibility of the wires allows an animal to move through vegetation with no substantial hinderance and adds very little weight. The hand-held detectors are relatively light and about 20×20×5 centimeters in size. One challenge with this technique is that the signal is more limited than traditional radio telemetry or GPS trackers, and depends on the size of the diodes and wires. The larger tags (with wires 0.08 millimeters in diameter and 16 centimeters in total length) provide a signal at a range of about 30 meters. Considering that it appears that the frosted dromo tiger beetle is restricted to the mowed and unvegetated roadsides, a signal distance of 3 meters might be sufficient to cover the entire roadside width. It also provides the distance to extend past the mowed section to determine if the beetles are using adjacent areas. These smaller tags are only 8 centimeters in length and the wires have a smaller diameter — roughly 0.08 micrometers in diameter (Figure 6).

These harmonic radar systems were originally developed for search and rescue missions following avalanches. Skiers have tags incorporated into their clothing or equipment and searchers can locate the tags through several feet of snow. This technology has already been used to track butterflies, fruit flies (larger species in Hawaii), and frogs.

Since most tiger beetle species inhabit areas with sparse vegetation, these areas often experience hotter temperatures than if there was more vegetation cover. It appears that the frosted dromo tiger beetle is most active during low light but warm conditions, which could be near dusk or midday with substantial cloud cover. These observations suggest that this species has particular thermoregulation requirements. To assess thermoregulation related to microhabitat use or behavior, it is important to record the habitat temperature as well as the tiger beetle's body temperature. Infrared thermometers offer the ability to point and shoot to quickly and accurately record ground temperatures. Handheld meters with temperature probes are also made small enough to take into the field and accurately record the temperature of the tiger beetle's thorax.

By utilizing these technologies, we can learn more about at-risk species. Species might have specialized habitat requirements, specialized thermal requirements, or both. Only after understanding habitat use and requirements can we start to implement effective management and conservation efforts.

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Acknowledgements:

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Conservationist's Vision for the Future

By Ethan Duke

Innovations and evolving science tools have played a key role in providing a sound basis for ecological management decisions. Aerial imagery, mobile field tools, and web based reporting, are routinely used now by land stewards to manage our infrastructure. Data today are collected analyzed and then shared at scales never dreamed of by conservation pioneers. These new methods do not wholly replace traditional surveys, but instead offer a more comprehensive and enhanced view to help further connect patterns seen on the ground with patterns revealed from above. High-resolution drone imagery is a literal change in vision.

History

Aldo Leopold's bold and clear visions that led to the innovative *Game Survey of the North Central States* (1931) pioneered the path for Missouri's "first approach to scientific wildlife management"—a study that took place from 1934–1936. This National Park Service project was funded under the auspices of the Emergency Conservation Work Program, and was completed just prior to the formation of the Missouri Conservation Commission (Nagel 1970).

Biologists, game wardens, and 3,000 Missourians contributed to those surveys, collecting data on wildlife and habitat. Delivery of the original vision, albeit analog, provided the first informational baseline on Missouri's wildlife resources. The result was a clear snapshot of the current state of wildlife and habitat that yielded focused inferences.

Today

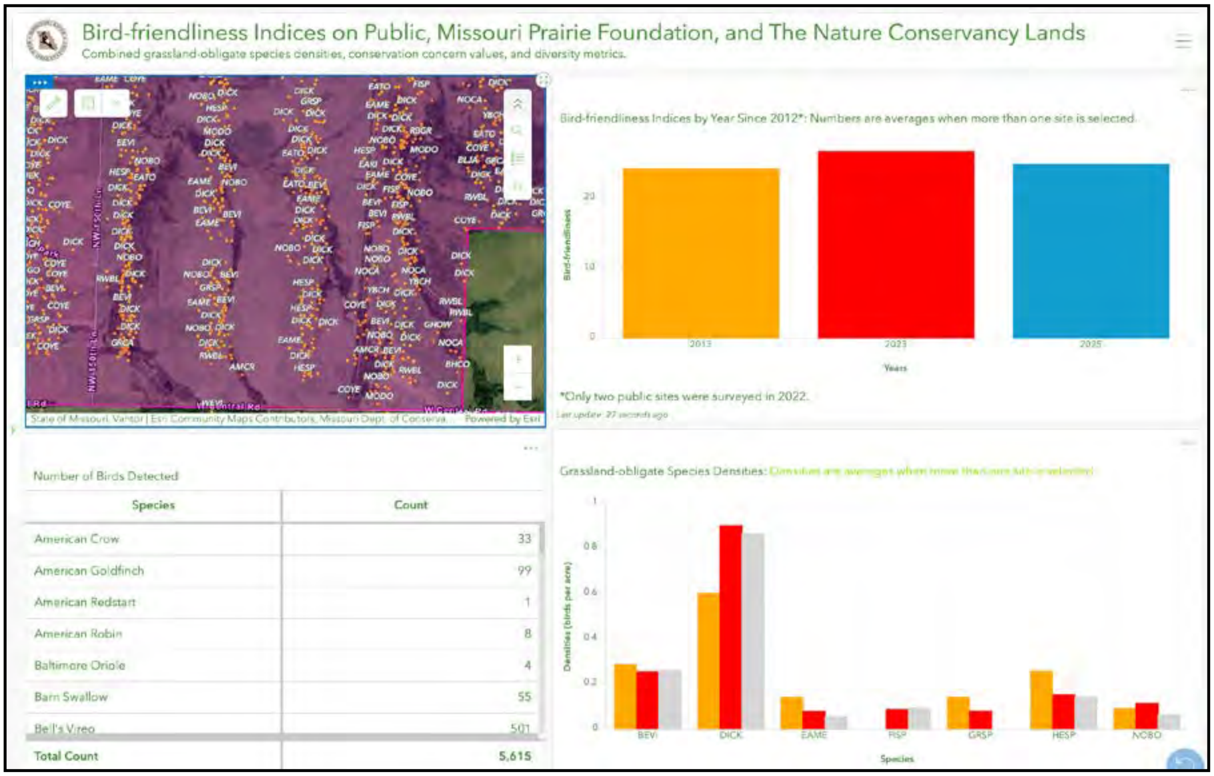
Recent work by the Missouri River Bird Observatory (MRBO) offers several examples of how approaches to modern workflows, including drone data aquisition, is used. In 2025, MRBO continued its long running grassland bird surveys across many of the state's remnant prairies, reconstructions, and grasslands. At the same time, we've collected aerial imagery that provides a clear view of habitat features often difficult to see without extensive ground work. The tools employed are now becoming commonplace, just in time when we need them most.

In 2012, MRBO began collecting spatially explicit data on every bird detection at multiple sites. For over a decade since, Line Transect Distance surveys have been used to document breeding birds across and beyond Missouri's priority grassland geographies. These surveys generate tens of thousands of spatially accurate detections each season. They form one of the most consistent records of grassland bird populations in Missouri and can display how species use habitats and respond to management actions. These data are available to researchers, practitioners, and the public in multiple formats via ArcGIS Online.

These results are now shared widely through interactive dashboards that serve many partners at once. Landowners, agency biologists, and local collaborators can explore species densities, annual trends, and site level summaries without waiting for formal reports. This format allows managers to see how bird communities change through time and how those changes align with their own management actions. The dashboards have become an important bridge between field surveys and real world decisions, and they demonstrate how biological information can be delivered in a clear and accessible way (Figure 1, next page).

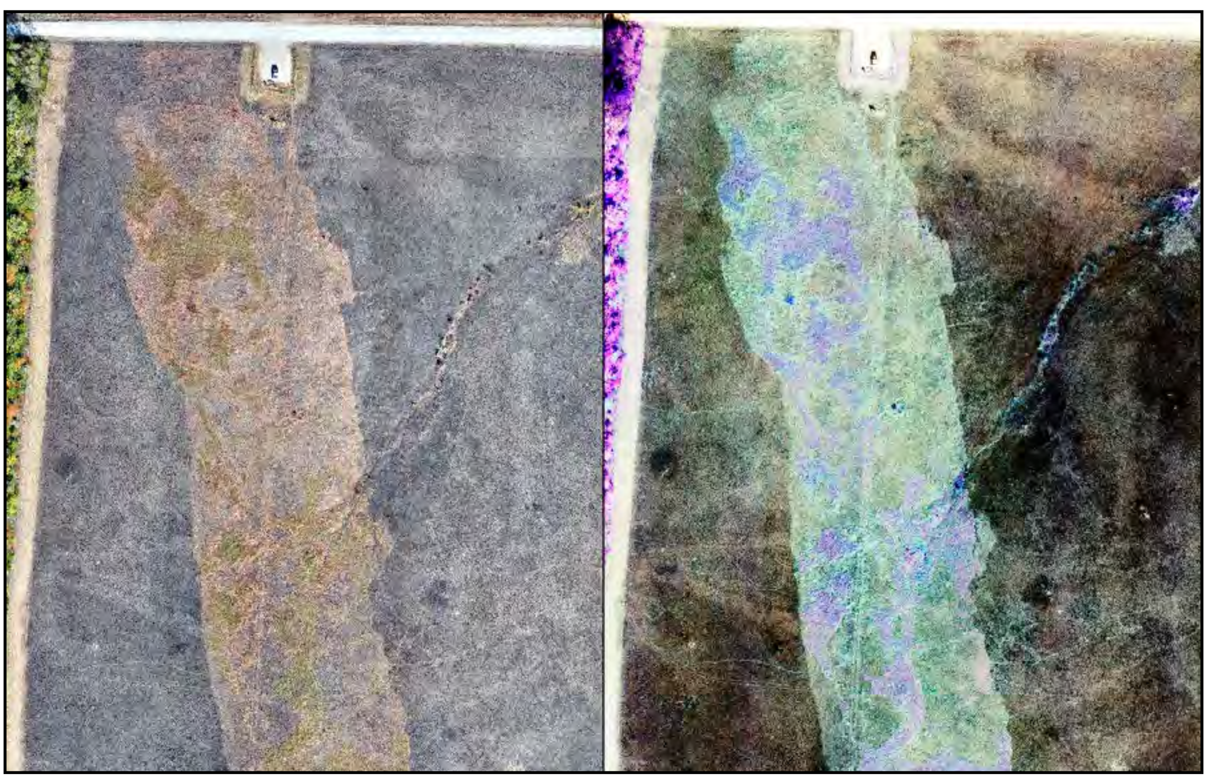
A New Vision from Above

In the past two years vegetation and habitat data were also captured with drone imagery. This added a new way of seeing the landscape. Burn patterns appeared as broad sweeping shapes across areas. Grazing effects created textured mosaics that varied in both height and density. Edges where an interspersion of woody species were beginning to advance became more apparent. Subtle differences in structure that affect bird occupancy can now be seen (Figure 2, next page.)



Missouri River Bird Observatory

Figure 1. A screenshot of MRBO's public facing bird-friendliness dashboard visible at https://bit.ly/47uJD5v. Survey results containing over a quarter million bird detections and related analyses are delivered to multiple stakeholders in this format, providing data and insights to researchers and the general public alike.



ESRI

Figure 2. Orthomosaics provide clear visualizations of prescribed fire at Paint Brush Prairie in the Hi-Lonesome grassland priority geography. The extent of the prescribed fire can be clearly seen in both RGB (left) and multispectral (right) views. Additional standard data include elevation models and point cloud data.

Missouri's biologists decipher and learn from drone data collection. Andrew Braun, Natural Resource Ecologist at Prairie State Park, instigated a drone mission that provided a striking example of the value of aerial imagery.

A fall flight was timed when warm season grasses were fading in color but certain woody and invasive species remained bright. In the layout seen here, false color frames on the left and natural color frames on the right revealed clumps of sericea and young sumac that were difficult to detect from the ground. Their late season color contrast stood out against the fading prairie and allowed managers to see patterns of establishment that had gone unnoticed. This success came not from advanced sensors but from knowing *when* to fly. Phenology created the contrast. With well-timed flights, land stewards can identify targets that appear only briefly each year. These moments open a practical path toward more precise and useful products for a variety of stakeholders and their purposes. Repeating such flights will allow us to track how these species expand or contract through time and how management actions influence their spread.

Strategic and methodical applications of this technology requires aggregating ecological expertise. It is crucial for numerous experts to weigh in and help lay the groundwork for Drone work, as it is for of other technological applications (Figure 3).

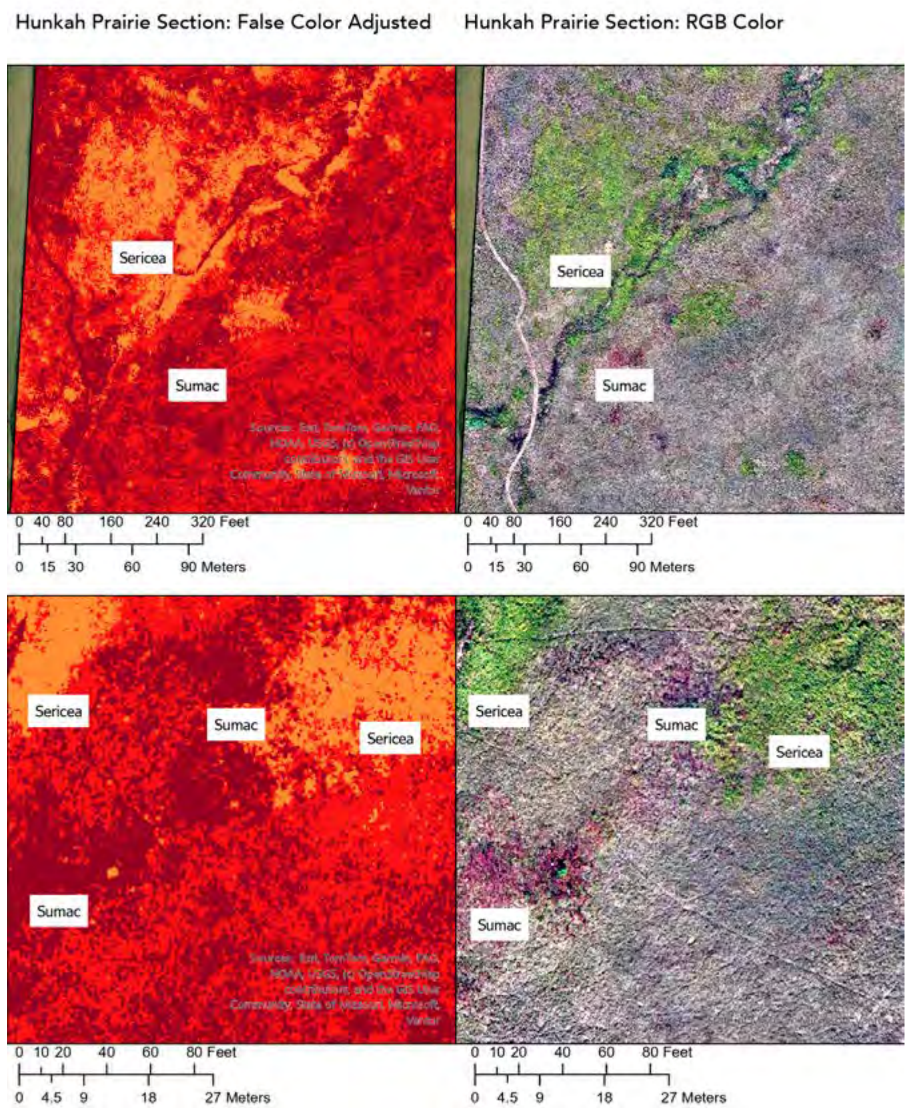


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Figure 3. Seen from above, the late fall prairie tells a different story than in other seasons. Sericea and young sumac hold their color while native grasses fade, and the contrast becomes clear in the false color frames on the left and the natural color frames on the right. These images offer an early look at how aerial tools can support stewardship. With careful seasonal flights, managers will one day be able to measure the acres of invasive plants, follow their spread through time, and judge the success of control efforts. The same information could appear in shared dashboards that help everyone who cares for grasslands understand how these landscapes are changing.

The Future

Nearly a century ago, conservation pioneers devised the four fundamentals of a successful game restoration and management program: administration, research, training, and public relations.

This concept holds true to this day. Training is a key component and those being trained in conservation fields now have the tools to intersect with the other three fundamentals.

Only now, that training should incorporate the utilities of the powerful tools we now have at the ready. The tools need to be harnessed by those with an ecological understanding to provide the most useful products for decision makers.

Not all ecologists have strong technological aptitudes or interest, but their perspectives, ideas, and insights are crucial. Whether working on study design, collecting and analyzing data, or producing measurable results, knowing these tools are part of the future of conservation work is essential. Further, the work of conservationists can now be scaled and shared more broadly and effectively than ever.

Toward a Shared Ecological Record for Missouri

One of the most promising developments is the potential to share data widely. Missouri has a strong tradition of cooperation among agencies and organizations. Many of the needed tools are already in place. Field staff use mobile data collection tools. Survey results are accessible through dashboards and the ArcGIS Online platform.

Similarly, and with coordination, Missouri could build a statewide archive of imagery and biological data that grows with each field season. Such a resource could live in MSDIS or a similar platform that encourages long term use. Students, researchers, landowners, and managers could explore these landscapes together. Natural area managers could compare sites and conditions. Restoration planning would be supported at a more granular scale. Over time, this system could also show how well treatments are working and track the acreage of invasive species across entire grassland complexes.

2026 Event Calendar

JANUARY 25–28, 2026

Midwest Fish & Wildlife Conference

Fort Wayne, Indiana • midwestfw.org

JANUARY 28, 2026 • 4–5PM

Missouri Prairie Foundation Webinar

"Wiski/Oski (River Cane): A Keystone Species in the Floodplain and in Chickasaw Culture"

tinyurl.com/kcwnyye9

JANUARY 31, 2026 • 10AM–2PM

Audubon Center at Riverlands

"Eagle Saturday" — spend the day viewing wintering Bald Eagles along the Mississippi River

West Alton, Missouri • tinyurl.com/3swvv6u8

FEBRUARY 3–5, 2026

Missouri Natural Resources Conference

"Innovation Conservation"

Osage Beach, Missouri • mnrc.org

FEBRUARY 17, 2026 • 11AM–12PM

Missouri Botanical Garden

Member Speaker Series: "Hidden Figures: Women Honored in Plant Names"

St. Louis, Missouri • tinyurl.com/pvw2baww

MARCH 30, 2026 • 6:30–7:30PM

Missouri River Bird Observatory

Winter Webinar Series: "Grassland Birds with Alice Boyle"

Registration: tinyurl.com/5dwcuc43

AUGUST 21–22, 2026

Missouri Bird Conservation Initiative Conference

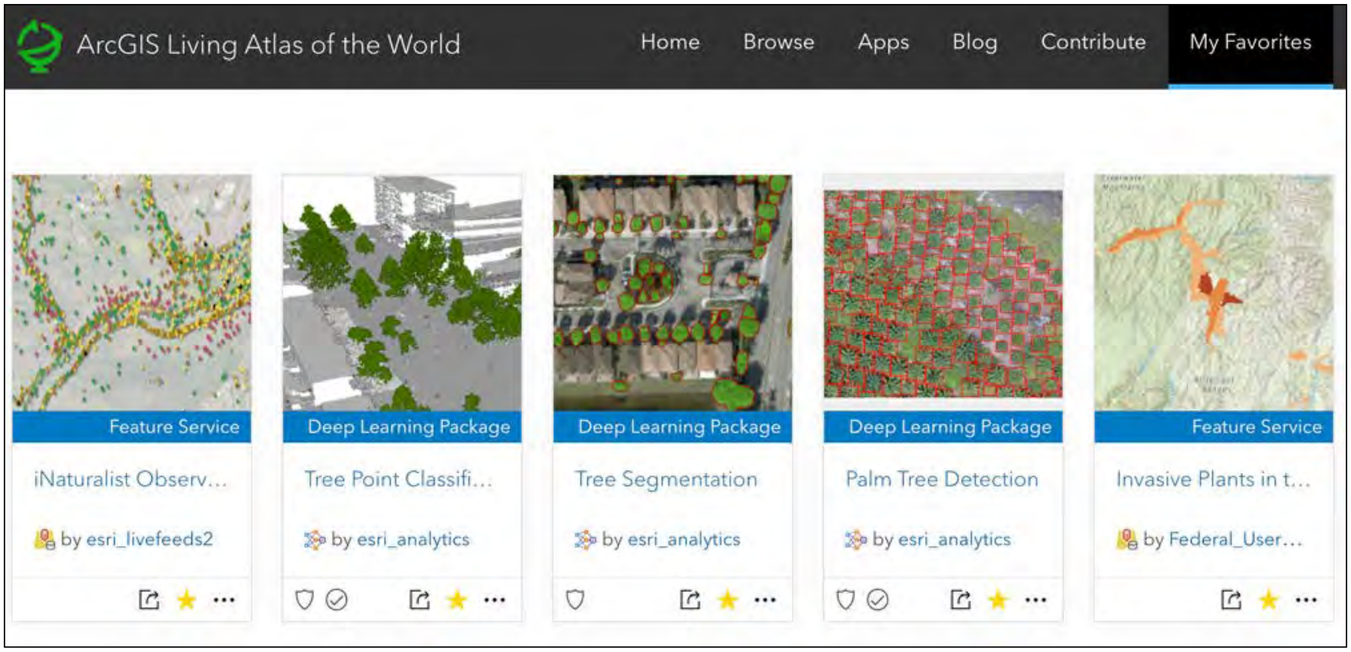
Columbia, Missouri • Mobci.net

OCTOBER 5–8, 2026

Natural Areas Association Conference

"Where Science Meets Stewardship"

Asheville, North Carolina • Naturalareas.org



ESRI

Figure 4. A screenshot of a few of ESRI's Living Atlas Pre-trained Deep Learning Models. These models can be used to automate the detection of targets captured by imagery.

Looking Forward

Imagine where this work will lead! In the next few years drone-derived aerial imagery will become routine for documenting prescribed burn extents, grazing impacts, and patches of invasive species. In only a few years Missouri could have a complete and regularly-updated baseline of its major prairies and grasslands. In less than a decade the state could maintain one of the most complete ecological archives in the country, accessible to anyone who wishes to understand or care for these places.

The uses of these data are unlimited. Machine learning and deep learning models are already accelerating the mundane work on which ecologists of the past deemed as necessary. ESRI's Living Atlas provides a glimpse at this potential. Pre-trained deep learning models have already been created for a variety of purposes to automate tasks such as counting plants and animals from remote imagery. Leaning into Missouri's vast repository of ecological expertise, one can only imagine the possibilities of quickly quantifying plants and animals in our natural communities.

MRBO is currently working on pre-training deep learning models for identifying and quantifying invasive species from drone data (Figure 4).

Our work shows that this future is within reach. Field biologists continue to gather the information that defines the character of each natural area. Aerial imagery adds the broader view that helps interpret those observations. Together they create a clearer picture of how these landscapes function and how they change through time.

Missouri has led in conservation innovation before. With thoughtful use of modern tools and a shared commitment to documenting our natural areas, our state can lead well into the future. This work, both on the ground and in the air, will help ensure the continuance and furtherance of the vision for successful stewardship of our natural areas for the generations that follow.

Ethan Duke is Director and co-founder of the Missouri River Bird Observatory

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Citations:

Nagel, Werner O. 1970. *Conservation Contrasts: Three Decades of Non-Political Management of Wildlife and Forests in Missouri.* Jefferson City, MO: Missouri Department of Conservation.

Sinkhole Mapping Using LiDAR DEMs and Supervised Machine Learning Within the Mark Twain National Forest

By Joshua W. Hess, Marc R. Owen, and Tasnuba Jerin

Introduction

The U.S. Forest Service (USFS) manages the Mark Twain National Forest (MTNF) in southern Missouri and is in the process of updating soil/ecological resources maps and databases within the forest. Part of this effort is to improve outdated sinkhole inventory maps using high resolution elevation data, advanced geospatial analysis techniques, and enhanced geomorphic sampling and classification methods. The advancement and availability of Light Detection and Ranging (LiDAR) elevation products allows for the identification of surface depressions over large areas at a relatively fine scale (Rahimi and Alexander 2013, Qiu and Wu 2016). Various techniques have been developed recently to help automate, filter, and differentiate artificial, or human created features, from naturally formed sinkholes using LiDAR derived digital elevation models (DEMs) (Hesse 2010, Zhu et al. 2014, Wu et al. 2016). Further, morphological properties, landscape position, and other geospatially obtained metrics have been used to classify sinkholes for hazard mapping and identify areas for potential formation (Miao et al. 2013, Kuniansky 2016, Qiu et al. 2020). Federal and state agencies currently lack a complete sinkhole mapping database that can be used to assess forest lands, inform management plans, support watershed protection, better understand groundwater recharge, identify geological hazards, and protect critical areas in Ozark landscapes.

PURPOSE AND OBJECTIVES

To help address this gap in sinkhole data and analytical capacity, the USFS hired the Ozarks Environmental and Water Resources Institute at Missouri State University to complete a sinkhole mapping project within the six ranger districts of the MTNF and the area immediately surrounding the Doniphan/Eleven Point (DEP) Ranger District in southern Missouri. The total project area is over 12,000 km^2 (3-million acres), so an automated process was developed and tested to map sinkholes over a large geographic area. The purpose of this project is to use available LiDAR elevation data to map sinkholes within the MTNF using advanced geospatial techniques. Specific objectives of this study are: (i) identify all significant closed depressions within the MTNF using high resolution DEMs, (ii) distinguish naturally formed sinkholes from artificial depressions using supervised machine learning, and (iii) quantify accuracy using a combination of geospatial and field-based verification techniques. The final product of this study is a geospatial sinkhole database for the entire MTNF with accuracy at an acceptable confidence interval that can be used to inform forest management decisions.

Project Area

The MTNF covers over 9,200 km^2 of Forest Service owned and non-Forest Service owned land in 29 counties within Missouri. The study area for this project includes all land within the MTNF ranger district boundaries and an additional area surrounding the DEP Ranger District referred to as the Doniphan-Eleven Point Greater Area (DEGA) (Figure 1, next page). Forest Service lands comprise a little less than half the area while the remaining is mostly private land, with some other publicly owned lands making up the remaining area within the MTNF district

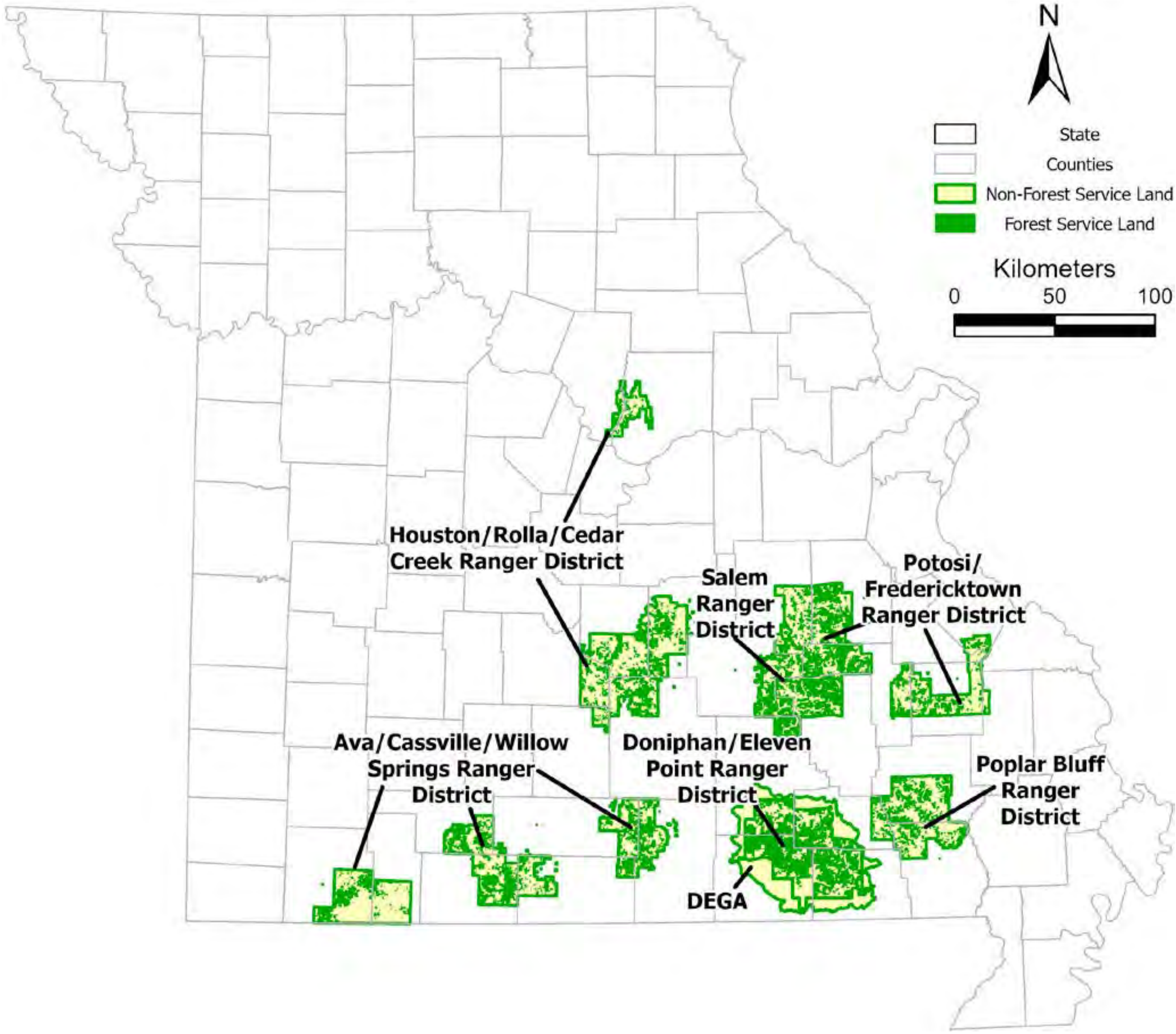


Figure 1. Mark Twain National Forest Ranger Districts in Southern Missouri.

boundaries. DEGA adds an additional 1,681 km^2 of non-Forest Service owned land. In total, 10,924 km^2 were analyzed for sinkhole presence over a wide range of underlying geology.

Sinkhole Mapping Methods

Sinkholes across the MTNF were mapped using a combination of high-resolution LiDAR elevation data, geographic information systems (GIS), and supervised machine learning. LiDAR is used to identify subtle changes in ground elevation beneath forest cover, and GIS tools can map those patterns. Machine learning can then be used to automatically distinguish between sinkholes and other depressions such as ponds or road-beds based on the morphometric characteristics of the depressions.

The work was completed in several major steps:

1. Identifying surficial depressions in GIS.
2. Manually classifying a subset of those features.
3. Extracting shape and terrain characteristics.
4. Training a computer model (Random Forest) to recognize sinkholes automatically.

DEPRESSION DELINEATION

The first step was to map all surface depressions using DEMs derived from LiDAR data. One-meter resolution DEMs were obtained from the U.S. Geological Survey's 3D Elevation Program and, when necessary, from the Missouri Spatial Data Information Service. These DEMs were merged to create continuous surfaces for each ranger district, including a 50-meter buffer around each area. A common GIS "sink-filling" method was used to identify roughly half a million depressions across the MTNF. To remove features that were too small or shallow to be meaningful, a minimum threshold of 9 square meters in area and 0.3 meters in depth was applied. These values were based on input from Forest Service soil scientists and ecologists. Depressions that were very elongated (length-to-width ratio greater than 3) were also excluded since most sinkholes tend to be circular or oval in shape. Applying these filters reduced the total number of potential depressions to about 159,000 (Table 1).

SINKHOLE IDENTIFICATION

A series of "training areas" were created within each district representing about 10% of the total mapped depressions. These areas included a variety of local geologies and elevations to capture the range of conditions within the district. Within each training area, each depression was manually reviewed using high-resolution aerial imagery and LiDAR hillshade surfaces. Features clearly shaped by human activity—such as ponds with visible berms, quarries, or road drainage—were marked as non-sinkholes (Figure 2, next page). Natural features without signs of modification were marked as sinkholes (Figure 3, page 27). This classified subset provided the foundation for training the machine learning model to distinguish sinkholes and non-sinkholes within each district. To check the accuracy of the manually classified depressions, 892 features were evaluated both in GIS and in the field. The results matched extremely well with a 99.3% overall accuracy.

Because LiDAR does not penetrate water, some water-filled sinkholes might not appear as depressions. To address this, mapped depressions were cross-checked against the National Wetlands Inventory (Figure 4, page 28). Of more than 17,600 wetlands examined, 62 were confirmed to be actual sinkholes. In addition to the wetlands cross-reference a GIS check of deep (> 2 m) irregularly shaped (length to width ratio > 3) depressions was also performed to ensure that obvious (deep/large) non-conforming sinkholes were not missed (Figure 5, page 28). Following the same GIS interpretation methods, all depressions greater than 2 m deep and having length to width ratios greater than 3 were manually attributed as sinkholes or non-sinkhole depressions. In total 824 depressions met these criteria and were inspected. Only 17 were determined to be sinkholes.

Table 1. Pre-modeled surficial depression geometries and distribution.

Ranger District	Area (km^2)	>9 m^2	& >0.3 m Deep	& ELG < 3	Density (#/km^2)
Ava	1,173	27,123	13,040	8,275	7.1
Cassville	995	18,496	11,647	7,843	7.9
Cedar Creek	281	16,865	7,440	4,857	17.3
Doniphan-Eleven Point	2,045	71,685	29,339	18,203	8.9
DEGA	1,681	47,654	25,266	15,510	9.2
Fredericktown	946	25,301	12,300	7,280	7.7
Houston-Rolla	2,063	81,471	41,459	25,936	12.6
Poplar Bluff	1,373	61,907	26,161	15,338	11.2
Potosi	1,506	69,379	37,302	24,694	16.4
Salem	1,253	59,930	32,414	21,283	17.0
Willow Springs	796	26,271	14,867	9,732	12.2
Total	10,924	507,872	260,272	158,951	14.1

ELG = elongation ratio (length:width)

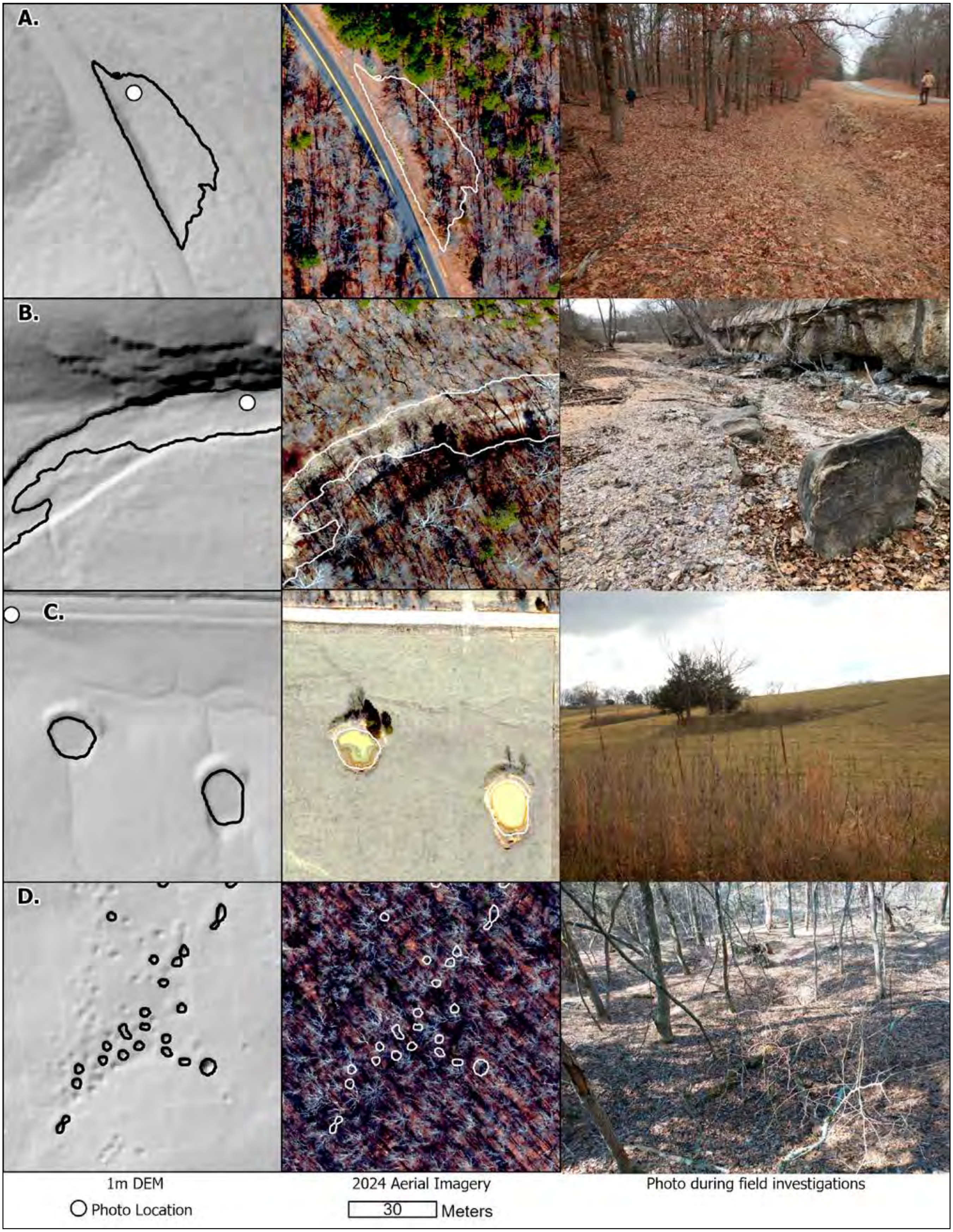


Figure 2. Examples of Non-Sinkhole Depressions. **A.** Road Ditch. **B.** Ephemeral Stream Valley. **C.** Ponds (with Berms). **D.** Prospect Mining Pits.

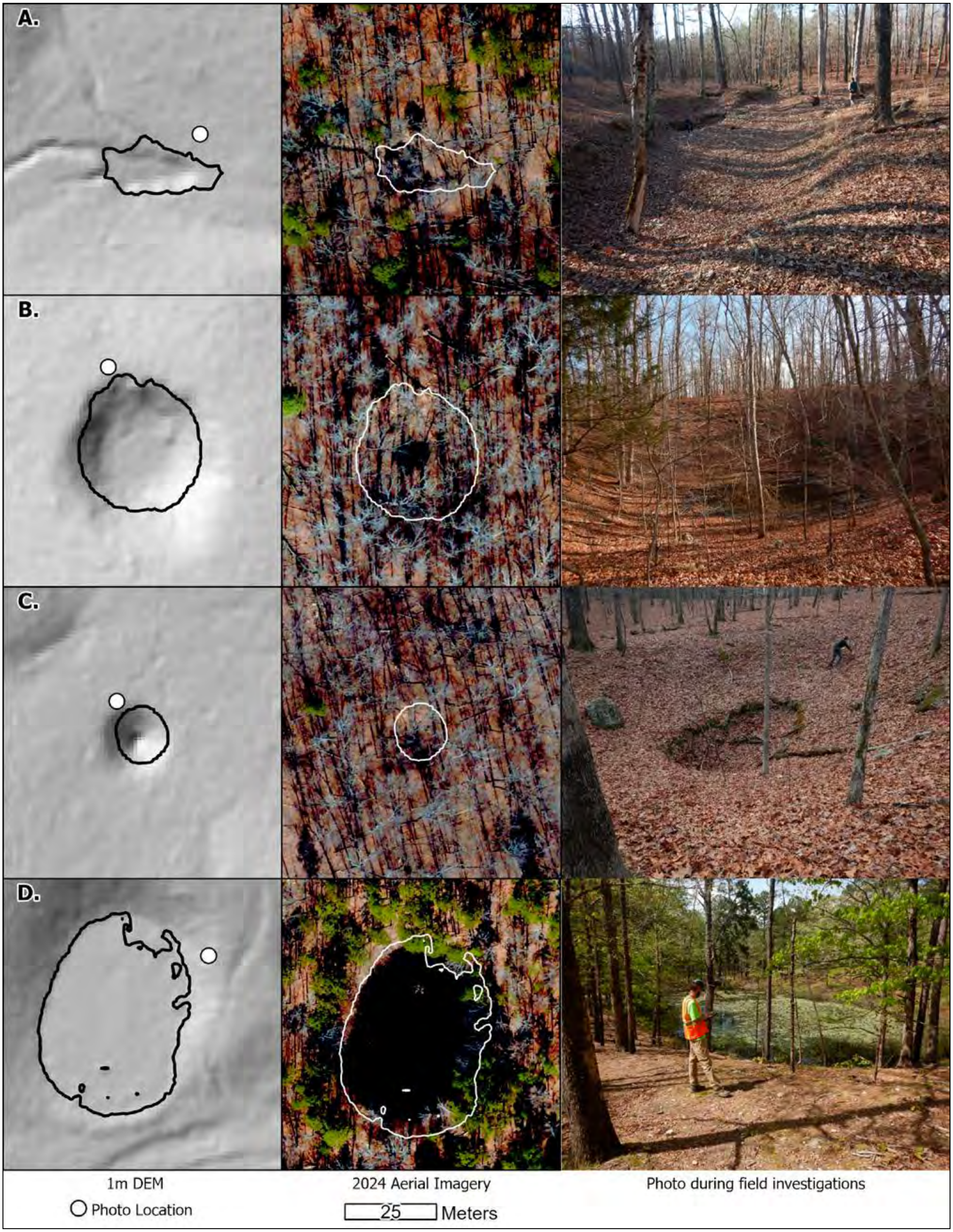


Figure 3. Examples of Sinkholes. **A.** Sinkhole in Valley Bottom (captures stream flow). **B.** Sinkhole on Hillslope with shallow water pool in bottom. **C.** Sinkhole on Hillslope with Vertical Collapse. **D.** Large Sinkhole with Standing Water.

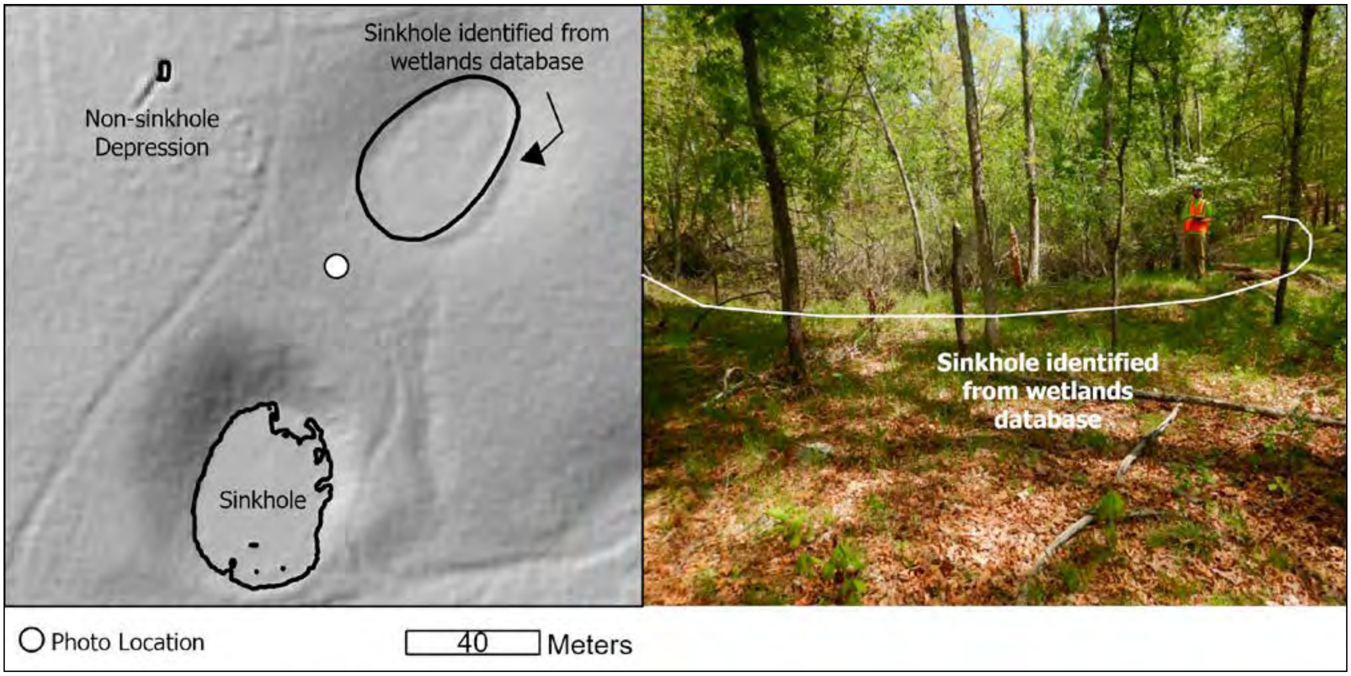


Figure 4. Wetland Sinkhole in the DEM and in the Field.

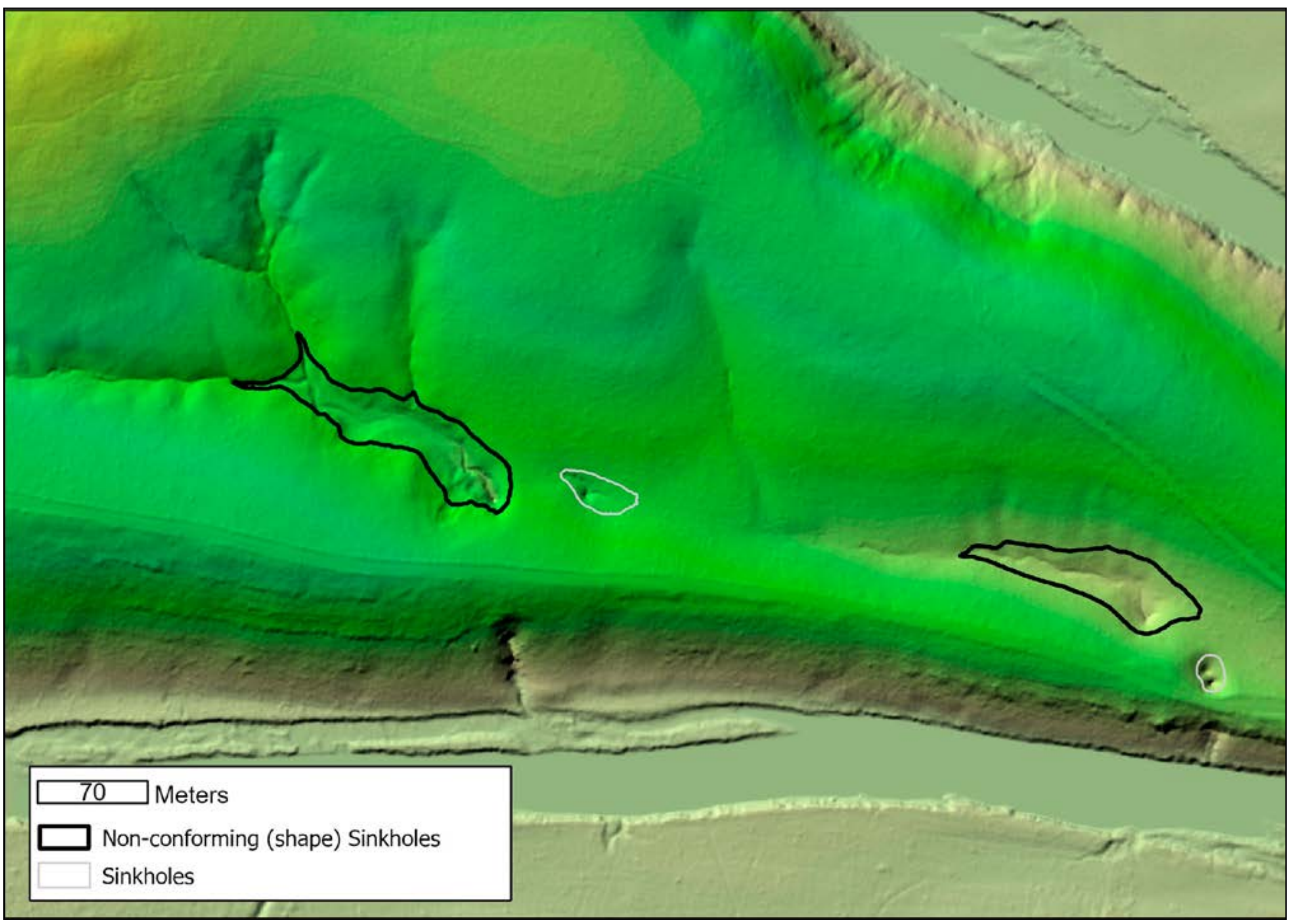
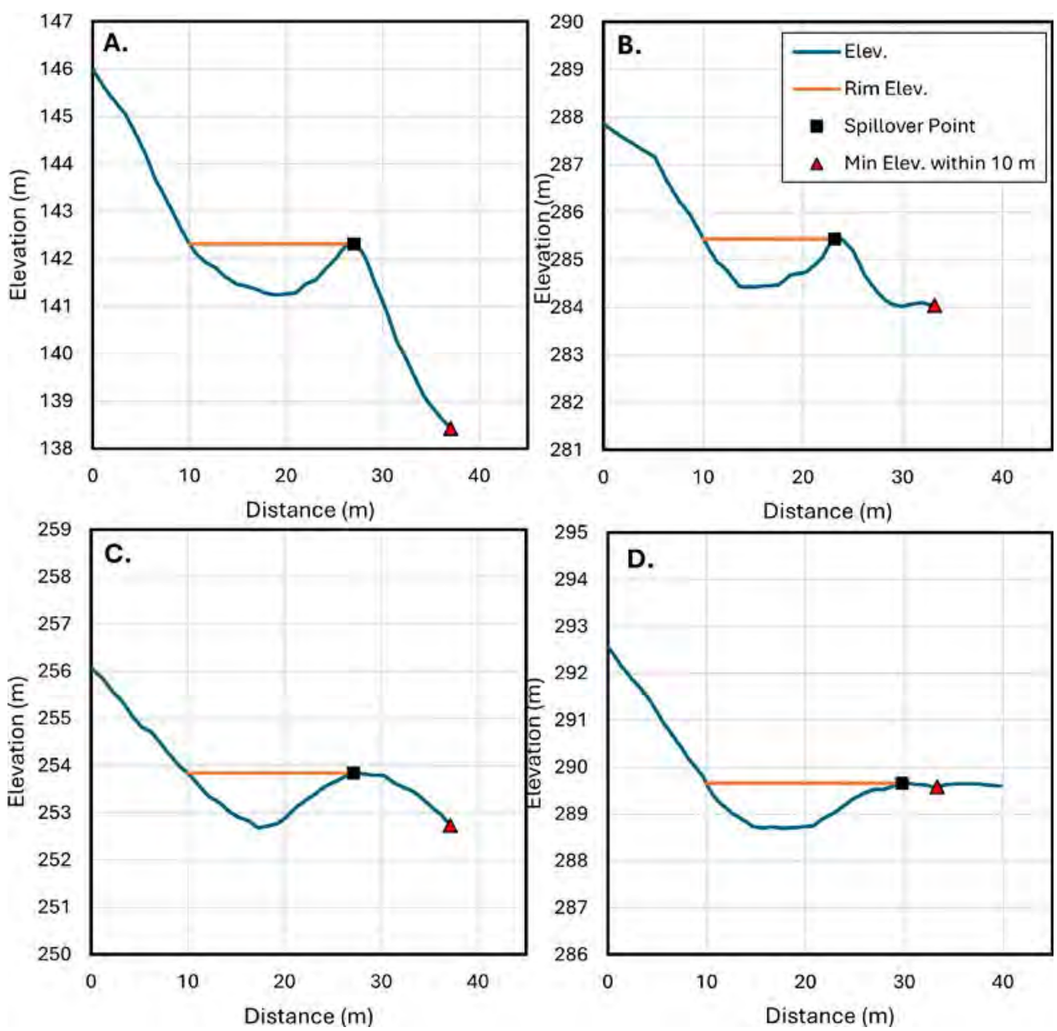


Figure 5. Irregularly Shaped (Elongated) Sinkholes.

DEPRESSION ATTRIBUTES

Each depression was attributed with morphometric and contextual attributes. These included area, perimeter, depth, volume, and compactness. Previous studies have found that sinkholes are typically deeper than non-sinkhole depressions, usually have a large area, relatively simple shape, and are not elongated (Miao et al., 2013; Wu et al., 2016). Additionally bottom roughness, clay percent, and average berm slope were used to assist in the identification of sinkholes (Miao et al., 2013; Zhu and Pierskalla, 2016; Wu et al., 2016). Where bottom roughness is the variance of the bottom of the depression, with higher variance associated with sinkholes (Miao et al., 2013; Zhu and Pierskalla, 2016). Soils with higher clay content have been found to be less prone to forming sinkholes due to higher soil cohesion (Zhu and Pierskalla, 2016). Berms refer to man-made features that impound water and thus create ponds. The berm slope variable is a method of identifying whether a berm exists around a depression by analyzing the average slope between the rim of the depression and a 10 m buffer around the depression (Zhu and Pierskalla, 2016). Furthermore, four new variables were also created to examine their usefulness in identifying sinkholes from non-sinkhole depressions: 1) drainage area; 2) width-depth ratio; 3) drainage area-area ratio; and 4) berm-drop. These helped distinguish non-sinkhole depressions from sinkholes and improved model accuracy. The berm-drop variable was specifically added to help distinguish man-made ponds (with berms) from sinkholes, as small ponds can have very similar morphometry (Figure 6). The model uses these variables to distinguish sinkholes from non-sinkhole depressions.

Figure 6. Surface depressions with a 10 m buffer on each side. **A.** Pond on hillslope. **B.** Pond on valley margin. **C.** Sinkhole on hillslope. **D.** Sinkhole on valley margin. For A–D, depression area ranged from 198.3–203.3 m^2 and max depth ranged from 0.78–1.8 m. (adopted from Jerin et al., 2025 — in revision).



RANDOM FOREST MODELING

For automated classification, a supervised machine-learning approach called Random Forest was used, which combines the decisions of many "trees" to reach a consensus—much like getting multiple expert opinions before deciding. Each tree evaluates a depression's characteristics (shape, depth, slope, etc.) and votes on whether it is a sinkhole or not. The model's final prediction is based on the majority of votes. This method is especially effective because it reduces over-fitting (a common modeling problem) and increases prediction accuracy across large, diverse datasets. While Random Forest aims to minimize overall classification error, it inherently treats all classes equally, which can lead to bias toward the majority class in imbalanced datasets. This is especially problematic in sinkhole mapping, where true sinkholes are often outnumbered by non-sinkholes. In such cases, a model might achieve high overall accuracy while failing to correctly identify minority class instances. To address this issue, we implemented data balancing techniques prior to model training.

DATA BALANCING

One challenge in this kind of work is that there are usually far fewer sinkholes than non-sinkholes, which can bias the model. To correct this imbalance, we used data balancing techniques that create or remove examples to even out the two categories. Two common methods—ROSE (Random Over Sampling Examples) and SMOTE (Synthetic Minority Over-Sampling Technique)—were tested, and the best results were used for each district. Districts with similar geology were also combined to improve performance. For example, data from the Ava, Cassville, and Doniphan-Eleven Point districts were grouped to strengthen the model for those areas.

APPLICATION OF THE RFM

After training and balancing the data, the Random Forest model was applied to all remaining depressions across the MTNF. Each was classified as either a sinkhole or a non-sinkhole. Accuracy was tested through GIS verification using randomly selected samples within each district. Across the forest, district models achieved greater than 85% overall accuracy (Table 2). The model "accuracy" is a measure of how well the model classified sinkhole and non-sinkhole depressions. This ranged from 75%–97% across districts. However, the "true positive rate" is a measure of how well the model identified actual sinkholes.

Table 2. Random forest model results for each district.

Ranger District	Ranger District Area (km^2)	Total GIS-Verified Sinkholes	Total GIS-Verified Non-Sinkholes	Overall Model Accuracy (%)	True Positive Rate @ >0.3 m (%)	True Positive Rate @ >0.5 m (%)	True Positive Rate @ >1.0 m (%)	Total Mapped Sinkholes	Sinkhole Density #/km^2
Ava	1,173	243	1,458	87.6	83.5	88.1	89.5	1,239	1.1
Cassville	995	43	1,378	91.1	73.7	84.6	87.5	787	0.8
Cedar Creek	281	36	548	96.7	83.3	80.0	100	199	0.7
Doniphan-Eleven Point	2,046	785	2,429	84.5	86.0	93.6	96.4	4,444	2.2
DEGA	1,135	106	894	83.9	89.6	96.3	100	3,124	2.8
Fredericktown	946	17	890	94.6	100	100	100	515	0.5
Houston/Rolla	2,063	288	2,454	92.8	92.9	90.9	100	3,265	1.6
Poplar Bluff	1,373	30	1,475	75.2	100	100	100	264	0.2
Potosi	1,506	19	2,908	96.2	50.0	50.0	100	836	0.6
Salem	1,253	45	3,039	85.2	78.1	77.4	80.0	1,030	0.8
Willow Springs	796	124	987	87.2	85.7	100	100	1,263	1.6
Total	10,924	1,736	18,460	86.6	85.8	92.3	94.3	16,966	1.6

"Accuracy" = how well the model identified sinkholes and non-sinkholes combined
"True Positive" = how accurately the method identified actual sinkholes

The overall true positive rate for sinkholes that are >0.3 m deep was 85.8% and varied from 73.7% to 100% across all districts. The difference between the model accuracy and the true positive rate was influenced by the number of false positives in the dataset. A "false positive" meaning the model misclassified a non-sinkhole. Further, the true positive rate improved as depression depth increased suggesting shallower sinkholes are harder to identify using these methods. All district models for depressions >1 m deep achieved a true positive rate ≥80% and 94.3% overall.

Final Sinkhole Database

The final database includes 16,966 mapped sinkholes, compared to only 888 previously known features—nearly a 20-fold increase in identified sinkholes. Each sinkhole record contains information about its shape, geology, surrounding land use, confidence level, and if it was verified by GIS or through field work. Using advanced mapping technology and computer modeling, this project created the first comprehensive sinkhole database for the MTNF. The results show that automated methods can reliably identify natural sinkholes even in complex terrain, providing a valuable tool for land management, watershed protection, and hazard assessment. This helps ensure adequate protection of sensitive landscapes and essential ground water resources in the Ozarks.

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Photo courtesy of Jennifer Veith/Carpenter Nature Center.

Figure 1. A Wood Thrush perched in a tree in its habitat of mature deciduous forests, in Wisconsin.

International Wood Thrush Motus Project Continues

By Sarah Kendrick

In 2024, a multi-national group of bird-conservation partners across the hemisphere initiated a massive research project to track the survival and migration of Wood Thrush across the breeding and nonbreeding ranges. This effort occurred in 2024–2025 to target conservation efforts for the species—an important forest-breeding bird (Figure 1).

Between May and July 2025, with Colombian bird-conservation organization SELVA, I coordinated over 60 partners to deploy over 990 Motus Wildlife Tracking System tags on Wood Thrush in 27 U.S. states and Ontario across the species' breeding range. SELVA coordinated the tag deployment of over 140 more Motus tags in five countries of the species' nonbreeding range this past winter, making our effort the largest Motus project to date.

The Wood Thrush *(Hylocichla mustelina)* is a medium-sized songbird of Eastern deciduous forests known for its flute-like, ethereal, ee-oh-lay song. The Wood Thrush is a long-distance Neotropical migrant, meaning it spends over half the year in tropical forest from Mexico to Panama. This thrush acts as a flagship species for full annual cycle conservation work in the Neotropics because they require a mid-elevation forest structure on nonbreeding grounds that is also needed by many other forest-breeding migratory songbirds. Full annual cycle conservation means working to identify and address threats that migratory birds face through all stages of their year, including breeding stage, migration stages, or nonbreeding stage.

The Motus Wildlife Tracking System (Motus) is an international collaborative research network that uses

Figure 2. Motus stations like this one at Stegall Mountain Natural Area in Missouri use antennas to detect the signals emitted from Motus tags attached to birds within range of a station.

coordinated automated radio telemetry to facilitate research and education on the ecology and conservation of migratory animals (Figure 2). Motus[1] is a program of Birds Canada in partnership with collaborating researchers and organizations.

With over 1,100 tags deployed on the species over its full range, we will better understand Wood Thrush migratory connections, routes, timing and survival across the full annual cycle to inform conservation action. The Wood Thrush is a priority species for conservation in 25 states and holds threatened status in Canada. Improving our understanding of the ecology of this species' full annual cycle is essential to better understand conservation needs throughout its range and to improve the design of targeted habitat management actions. The hemispheric Motus-tagging research and conservation project will help us to better understand migratory connections, routes, timing and survival across their full annual cycle.

In spring 2023, I approached state wildlife agencies via the Nongame Bird Technical Sections of the Mississippi and Atlantic Flyway Councils to ask if they were interested in being part of a large-scale research study on Wood Thrush. The project goals were to tag the species with Motus tags across their breeding range in the eastern U.S., in partnership with SELVA, who would coordinate Motus-tagging in Mexico, Belize, Guatemala, Honduras, Nicaragua and Costa Rica. The pitch was that, if states or organizations could commit the funds for 25 tags and coordinate the deployment of those tags on Wood Thrush in their state with permitted taggers, I would handle the coordination and logistics of the project, and we could do something at an unprecedented scale to learn a lot about the species together. To my surprise, many states and federal agencies and other organizations signed onto the project to participate! Mass planning commenced.

1 https://motus.org

Photo by Sarah Kendrick/USFWS

Figure 3. A Wood Thrush fitted with a Motus tag.

Our partner SELVA and I wrote a common (and required) project protocol to ensure that all project partners were using the same field methods, Motus tags, attachment harnesses and bird-handling permitting process (Figure 3).

The Motus tags deployed on Wood Thrush have batteries that last nearly 1.5 years, allowing us to gather up to three migratory seasons of data and allow us to examine inter-annual survival, which can be difficult to study in migratory species.

Many aspects of this project are providing us a positive proof of concept, including its scope and scale, and unique funding streams. A number of private, in-state funding streams are helping numerous states fund their project's Motus tags or field work, making this massive project largely a grassroots-funded effort. Multiple birding groups in Missouri, including the Missouri Birding Society, Burroughs Audubon Society, Columbia Audubon Society and other private donors funded Missouri's Motus tags and a Motus station for the project.

Data have been pouring in since May 2024 when tagging began. Field work wrapped up in summer 2025, but another year's worth of data remains to be collected from nearly 500 Wood Thrush tagged this past summer across their breeding range. After that, we hope our project's analysis will give us new insights into Wood Thrush survival and migration, allowing us to better deliver conservation for this iconic Eastern-forest bird.

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Advancements in Genomic Technologies: Unlocking New Pathways for Conserving Endangered Species

By Christine E. Edwards, Wen-Hsi Kuo, and Brigette Williams

The idea that genetic information could inform conservation started over 50 years ago when Frankel (1974) described the 'urgent need for the exploration and clarification of the genetic principles of conservation.' The field of conservation genetics didn't gain traction until the 1990s, when the number of studies began increasing at a rapid pace (Hoelzel 2024). Now, conservation genetics is a well-established, applied subfield of population, evolutionary and quantitative genetics, with several textbooks written on the subject (Allendorf et al. 2022; Frankham 1995; Frankham et al. 2010). The overall goal is to use genetic information to provide insight into the diversity, reproduction, ecology, and evolutionary history of endangered species and to devise strategies to conserve them both in wild populations and in ex situ collections.

Initially, because it was very expensive and time-consuming to generate DNA sequences and genotype data, early empirical conservation genetics studies sequenced or genotyped only a few DNA regions or genetic markers from a few individuals (i.e., using a single DNA region or genotyping individuals using allozymes). The inferences that could be drawn from these data were somewhat limited, but generally they could be used to infer evolutionary relationships, measure genetic diversity, assess how genetic variation is structured across the landscape, and provide a rough estimate of inbreeding and effective population size.

Over the past 20 years, however, the ability to generate DNA sequencing data has experienced a revolution. Starting around 2005, advances in DNA sequencing technologies have dramatically increased the amount of DNA sequences that can be generated at once, while simultaneously reducing the cost. For example, high-throughput DNA sequencing technologies such as long-read PacBio sequencing and HI-C sequencing (which provides insight into three-dimensional structure of a genome) can be used to generate high-quality reference genomes for non-model species for less than $10,000, making genomics-scale data within reach for studying non-model species or those of conservation concern. Model species are a well-studied organism, like Arabidopsis thaliana, rice, or Brachypodium, chosen for its manageable characteristics (small size, fast life cycle, easy genetics) to understand fundamental biological processes. Similarly, it is now possible to use Illumina high-throughput DNA sequencing technology to generate billions of DNA sequences of up to 150 base pairs (bp; e.g., cystosine and guanine) in length in a single DNA sequencing run for only a few thousand dollars.

As the ability to generate genomic-scale data has become cheaper and easier, the range of questions that can be addressed by such data has also grown dramatically. Molecular biologists have developed a variety of protocols to build DNA sequencing libraries that are tailored to answer specific questions about organisms. Each of these approaches has been accompanied by corresponding advances in bioinformatics and data analysis that provide a framework for interpreting and applying the data to inform conservation. **Here, we will describe how different applications of high-throughput DNA sequencing technologies and corresponding analytical approaches have led to advances in our ability to understand the biology of endangered species native to Missouri and surrounding regions and inform conservation and restoration efforts.**

Reduced-representation sequencing provides cost effective genotype data that can be used for both population genetics and systematics

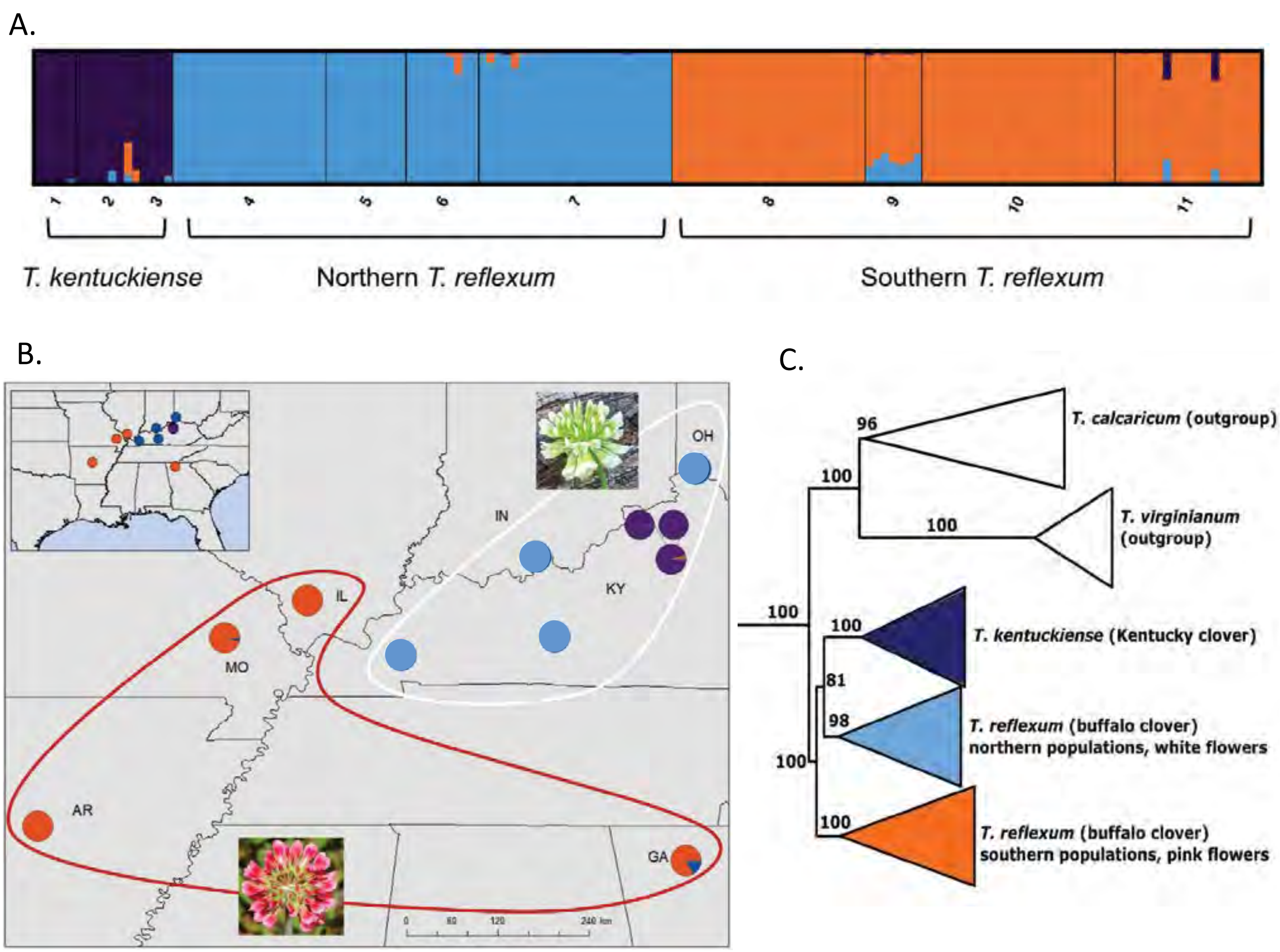
One of the first types of genomic-scale data to be used for species of conservation concern was reduced-representation sequencing. Reduced-representation sequencing is an approach often used to answer questions related to genetic diversity, genetic structure, or phylogenetic relationships. The two main types of reduced-representation sequencing are restriction-site associated DNA sequencing, or RAD-seq, and genotyping-by-sequencing (GBS) (Davey et al. 2011). Both techniques produce single nucleotide polymorphism (SNP) datasets, where individuals vary at a single base position in their DNA (for example, some individuals in a species might have an adnenine at a site in the genome, whereas others may have a cytosine at the same site). Both techniques are used to reduce the portion of the genome sequenced to only those DNA regions associated with cut sites of restriction enzymes. The number of DNA regions sequenced using these approaches depends on the genome size of the organism and the frequency at which a restriction enzyme cuts (Davey et al. 2011), but in general, these approaches result in datasets containing thousands of SNPs from across the genome of an organism.

One midwestern endangered plant that we analyzed using reduced-representation sequencing is Kentucky clover *(Trifolium kentuckiense;* Fabaceae). Kentucky clover is a recently described, critically imperiled (G1S1) species of clover with white flowers that is known from only two sites within Franklin and Woodford counties, Kentucky. In its original description, Kentucky clover was described as being morphologically similar and likely closely related to buffalo clover *(Trifolium reflexum)* based on both having a biennial life cycle, large leaflets, and inflorescences with similarly sized flowers, but Kentucky clover was differentiated based on its having decumbent stems (vs. erect or ascending stems in buffalo clover), wider stipules, shorter sepal lobes, longer petioles, and a different soil substrate (limestone soils rather than acidic soils) relative to buffalo clover (Chapel and Vincent 2013; Koenig et al. 2022). Buffalo clover is an annual to biennial herb with flowers ranging from dark pink to white clustered in inflorescences on long peduncles, with a geographic range throughout eastern North America. However, many regional botanists and conservation biologists have questioned whether Kentucky clover is really a genetically distinct group that is deserving of protection or instead whether it might be a subpopulation of buffalo clover

To address the distinctiveness of Kentucky clover, we sampled leaf tissue from individuals from the remaining populations of Kentucky clover. We also sampled multiple individuals per population from populations of buffalo clover from across its geographic range in the midwestern and southeastern U.S., including individuals with both pink flowers and red flowers. We extracted DNA, conducted RAD-seq library preparation, and sequenced it using Illumina DNA sequencing. We analyzed the data to understand patterns of population genetic structure and also analyzed the evolutionary history of the groups using phylogenetic methods.

Results of the population genomic analyses revealed that Kentucky clover formed a unique group and that buffalo clover was divided into two groups, one containing the white-flowered plants that occur in the northern part of the species' range, and one containing the red-flowered plants in the southern part of the species' range (Figure 1A and 1B, next page). The evolutionary tree also showed that Kentucky clover formed a distinct group and that it was most closely related to the white-flowered northern group of buffalo clover (Figure 1C). The red-flowered group of buffalo clover in turn formed the sister group to the group containing the two white-flowered clovers (Figure 1C). Based on the concept of monophyly, which posits that a species should contain a common ancestor and all of its descendants, if we choose to recognize Kentucky clover, then buffalo clover is not monophyletic and taxonomic changes are needed to ensure species monophyly. We have two options: the first is to subsume Kentucky clover into buffalo clover, potentially by describing Kentucky clover as a subspecies of buffalo clover (i.e., *T. reflexum* subsp. *kentuckiense*), and the second option is to recognize Kentucky clover as a distinct species and split buffalo clover into two based on flower color and geography. However, irrespective of the taxonomic decisions, we find that Kentucky clover is distinct, whether it is recognized as a species or subspecies, and merits conservation efforts to prevent its extinction. We also found that populations of Kentucky clover have low genetic diversity and are likely highly clonal. These results highlight how reduced-representation sequencing can provide important insights into a species that are relevant for its conservation.

Figure 1. Patterns of genetic structure and phylogenetic relationships in Kentucky and buffalo clover. **A.** Assignment of each individual to genetic clusters. The lines represent individuals, which are grouped by sampling location, with population numbers indicated below each group. The colors indicate the genetic clusters, and the color of each line indicates the assignment of that individual to the genetic groups. **B.** The map shows pie charts indicating the assignment of each population of clover to genetic clusters as shown in Figure 1A**.** The large circles around the points indicate the flower color found in the populations. **C.** Maximum Likelihood phylogeny showing the evolutionary relationship between Kentucky clover and buffalo clover. Values on the branches indicate UltraFast Bootstrap support values.



Data visualizations by the authors

Whole-genome sequencing provides unparalled insights into a wide range of questions

Another approach for conducting DNA sequencing that can provide unparalleled insights about a species and answer a wide range of evolutionary questions is whole-genome sequencing (WGS). Like reduced-representation DNA sequencing, WGS provides insight into population genetic structure and evolutionary relationships, but it can also be used to provide many additional important insights that are relevant for the conservation of a species, including factors such as decreases in population size over time, whether populations have experienced genetic bottlenecks or inbreeding, and whether populations have a high genetic load. It can also be used to provide insight into the genetic basis of phenotypic traits or local adaptation to environmental variation.

To be able to use WGS data to answer questions about the evolutionary and demographic history of a species, it is first necessary to assemble a reference genome for the study species. Recently, the per-base cost of long-read DNA sequencing has decreased substantially, so that creating a reference genome for a study species can be accomplished for under $10,000 for one species or under $5000 each for several species. Although still expensive, this price makes the creation of reference genomes for species of conservation concern within reach.

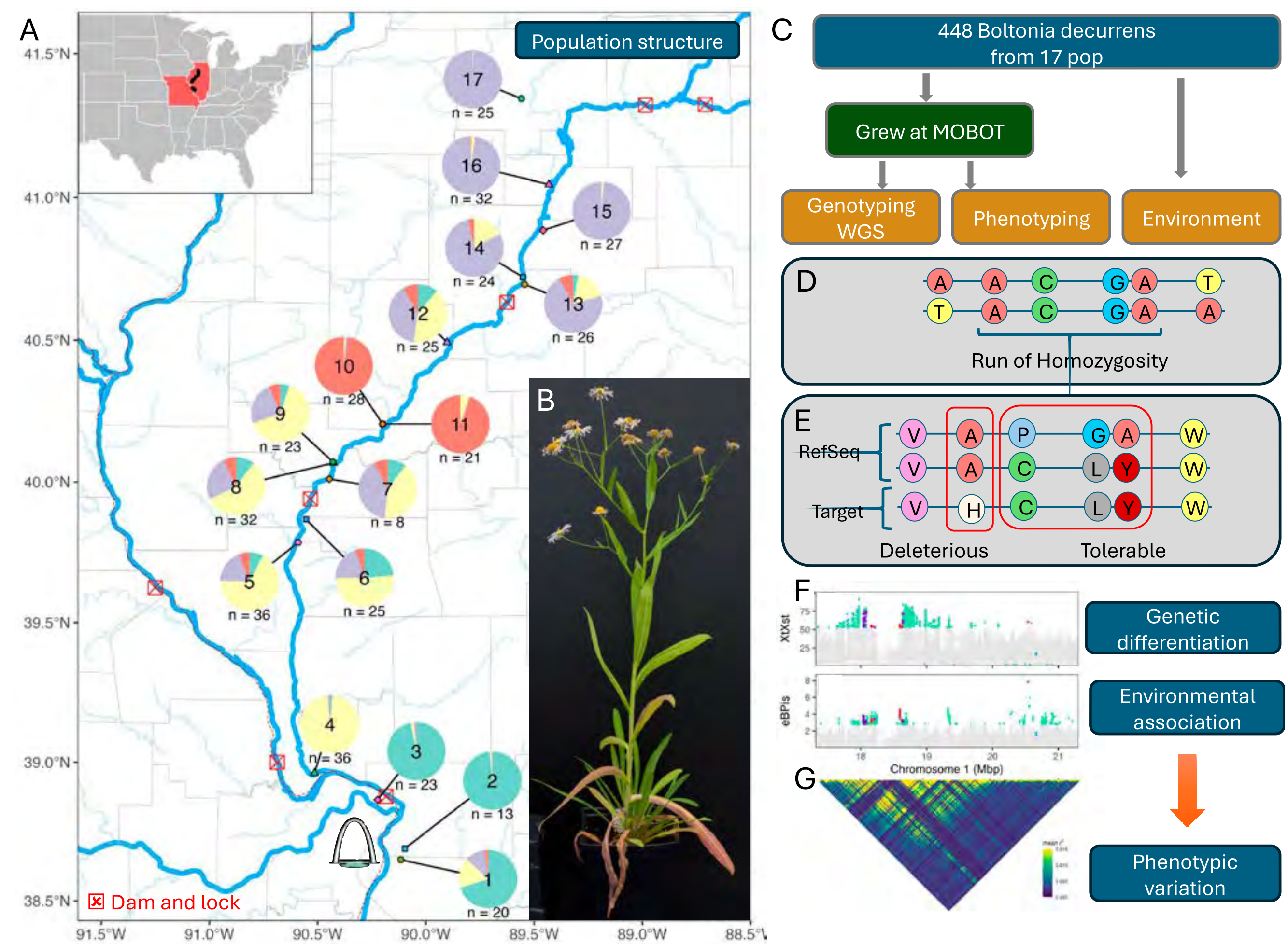
An example of a species in which we have used WGS to conduct a comprehensive conservation genomics assessment is decurrent false aster *(Boltonia decurrens;* Asteraceae). Decurrent false aster is a perennial herbaceous species that occupies flood plains along the Illinois and Mississippi rivers in Illinois and Missouri. It prefers open conditions created by floods occurring in winter and spring. Because of anthropogenic activities such as flood-control projects and destruction and degradation of the floodplain habitats that it occupies, decurrent false aster has experienced large declines, leading to it being listed as threatened under the US endangered species act. To inform conservation efforts for decurrent false aster, we conducted a comprehensive conservation genomic assessment. We grew plants of decurrent false aster from seed collected from 17 populations across the species range (Figure 2A and 2B, next page). We conducted PacBio long-read sequencing and Hi-C sequencing from one individual to build a reference genome, then generated whole-genome DNA resequencing data from hundreds of individuals (Figure 2C, next page). We also measured phenotypic traits of the individuals such as flowering time, plant height, and number of flowers produced (Figure 2C).

We analyzed patterns of population genetic structure in decurrent false aster, which generally showed a pattern of isolation by distance (Figure 2A), where populations that are geographically closer are more closely related. However, two populations in the center of the species range (populations 10 and 11) were genetically isolated from the remaining populations (Figure 2A), likely because they occur in a lake that is isolated from the main channel of the Illinois river so they don't experience gene flow with other populations. We also conducted an analysis of runs of homozygosity (ROH), which provides highly accurate estimates of population-level inbreeding without assumptions about expected allele frequencies (Figure 2D, next page). Results showed that populations 10 and 11 also showed the greatest inbreeding. We also conducted a model-based genetic-load estimation, where SNPs in coding regions were compared to the DNA sequencing database, RefSeq, which contains high-quality reference sequences that are well annotated with information such as protein coding regions, to identify mutations that change the amino acid product and may be deleterious (Figure 2E, next page). Both ROH and genetic load analyses can be used to identify populations in need of genetic rescue, where individuals from other populations are transplanted into those showing high inbreeding or genetic load to increase the genetic diversity and reduce inbreeding in the population. In decurrent false Aster, populations 10 and 11 showed both the greatest ROH and genetic load and may be good candidates for genetic rescue.

WGS data can also be used to understand the genetic basis of local adaptation to the environmental variation that a species' experiences across its geographic range We conducted genome scans of genetic differentiation and environmental association to identify genetic variants that may underlie local adaptation. Concordance between methods to identify variants underlying local adaptation allows us to identify candidate loci for local adaptation; ensuring that both natural populations and any ex situ collections maintain the allelic variation at these regions that may be critical for ensuring the long-term persistence of the species (Figure 2F). Regions potentially responsible for local adaptation can also be analyzed using a linkage disequilibrium (LD) heat map (Figure 2G). A block of elevated LD spanning two peaks (Figure 2G) suggests that it contains a gene that shows very low recombination and may harbor locally adaptive variation.

In summary, the WGS conducted in *Boltonia* has generated such a large amount of data that it rivals that generated for many model species. WGS can be used to provide a wide range of information about the species that is very useful for conservation; for example, we can use the data to ensure the conservation of the remaining variation in the species (both in wild and ex situ populations) and conduct population augmentations to remediate problems such as high genetic load and inbreeding.

Figure 2. Applying whole-genome sequencing (WGS) to plant conservation: a case study of Boltonia decurrens, a federally listed threatened species endemic to the Illinois River Valley. **A.** Population structure: pie charts show ancestry proportions per population, with colors denoting genetic clusters. **B.** Four-month-old *B. decurrens* at early flowering. **C.** Experimental design. **D.** Runs of homozygosity (ROH) from dense genome-wide markers used to estimate population-level inbreeding without assumptions about expected allele frequencies—useful when sample sizes are small or population structure is present. **E.** Model-based genetic-load estimation: coding variants are annotated against RefSeq to identify putatively deleterious amino-acid–changing mutations that can inform genetic-rescue or assisted-migration decisions. **F.** Genome scans of genetic differentiation and environmental association. Loci are colored by support: green, ≥99.9th percentile in either scan; red, intersection of the two scans; purple, intersection shared with two additional scans (not shown). Concordance between methods highlights candidate loci for local adaptation; maintaining diversity at these regions may be critical for long-term persistence. **G.** Linkage disequilibrium (LD) heat map. A block of elevated LD spanning two peaks suggests a ~0.5-Mbp structural variant centered near 18.2 Mb that suppresses recombination and may harbor locally adaptive variation.



Epigenomic variation provides a source of variation in species with low genetic diversity

Although the main goal of the field of conservation genetics is to measure and conserve the remaining genevtic diversity in an endangered species, many species have naturally low genetic variation because of aspects of their life history. For example, plants that reproduce asexually, either through vegetative reproduction or apomixis (i.e., asexual reproduction by seed), may result in a pattern where a large number of seemingly different individuals are genetically identical to each other. Similarly, plants that predominantly self-fertilize generally produce offspring that are nearly identical to their parents, producing low genetic variation among individuals but large differences among populations, because selfing causes strong genetic drift, enhancing differences among different selfing lineages. Furthermore, species that have small population sizes (like rare species) are more susceptible to forces that reduce genetic variation, such as inbreeding and population bottlenecks, and tend to have low levels of genetic diversity. Because genetic diversity is generally thought to promote resilience to environmental stress, populations with low genetic diversity are therefore assumed to be more vulnerable to environmental stress and at a greater risk of extinction than larger populations. However, many species, both rare and common, have low levels genetic variation, indicating that other factors beyond genetic variation may underlie species' responses to their environments.

One possible way that a species with low genetic diversity may respond to its environment, improving its likelihood of persistence, is through the combined effects of epigenetic variation and phenotypic plasticity (Williams et al. 2025). Phenotypic plasticity is ability of an individual to express different phenotypes in response to its environment. Plasticity is hypothesized to be caused by changes in gene expression within an individual rather than changes in the DNA sequence (Ecker et al. 2018). These changes in gene expression are in part achieved through epigenetic modifications such as DNA methylation, the addition of a methyl group to cytosines, which acts to decrease or silence expression of the gene. However, the role of DNA methylation in allowing threatened and endangered species with low genetic variation to persist in response to environmental stress is still poorly known.

To assess epigenetic variation, the newest and most informative approach is to use whole-genome bisulfite sequencing (WGBS). In WGBS, the similarities and differences in the proportion of methylated sites among individuals are analyzed to understand differences in methylation among individuals, populations, or species

One group in which we have analyzed whether variation and plasticity in DNA methylation and phenotypic traits allow them to respond to environmental stress is in four genetically depauperate species of *Leavenworthia* (Brassicaceae) native to the midwestern U.S (Williams et al. 2025). In this study, we focused on three diploid, self-fertilizing species: Michaux's gladecress *(L. uniflora),* necklace gladecress *(L. torulosa),* and Tennessee gladecress *(L. exigua* var. *exigua);* and one likely diploid apomict, Kentucky gladecress *(L. exigua* var. *laciniata)* (Figure 3, next page). The three selfing species show population genetic patterns typical of selfing, including low heterozygosity, low within-population genetic diversity, and high among-population genetic variation (Figure 3) (Beck et al. 2006). Kentucky gladecress is a subspecies of the predominantly self-fertilizing Tennessee gladecress, but likely reproduces asexually through apomixis (Edwards et al. 2022). Kentucky gladecress is diploid and shows nearly fixed genotypes across its geographic range (Edwards et al. 2022). Kentucky gladecress was included in the study both because it is federally listed as threatened under the U.S. Endangered Species Act and because it lacks genetic diversity, allowing us to investigate the link between variation in DNA methylation and phenotypic traits in the absence of genetic variation.

We grew individuals from several maternal lines and populations from each of the four species in contrasting watering treatments, measured phenotypic traits, and analyzed DNA methylation using WGBS (Williams et al. 2025). We assessed how patterns of DNA methylation differed within and among species, how phenotypic traits and patterns of DNA methylation varied in response to drought, whether variation in DNA methylation corresponded to phenotypic variation, and assessed the implications for conservation. We found that the four taxa were epigenomically distinct. Each species exhibited variation in both phenotypes and DNA methylation among populations (Figure 3) that could be relevant for conservation. Although this was expected in the three self-fertilizing species that exhibit among-population genetic variation, surprisingly, we found that Kentucky gladecress, which is apomictic and exhibits virtually no genetic variation among individuals or populations (Edwards et al., 2022), exhibited strong differences among phenotypes and epigenotypes from different maternal lines that were at least as great as differences found between populations of the three more genetically diverse *Leavenworthia* taxa (Williams et al 2025). Importantly, the U.S. Fish & Wildlife Service now considers these unique phenotypes and epigenotypes in Kentucky gladecress to be important new targets for conservation of this threatened species (USFWS 2022).

When comparing species response to drought, species differed in their DNA methylation and phenotypic responses to environmental stress, and the DNA methylation response to environmental stress corresponded to its phenotypic response (Williams et al. 2025). For instance, in necklace gladecress, we detected strong population structure both in the phenotypic traits and the epigenome that was maintained across treatments, whereas the widespread Michaux's gladecress displayed significant and concordant patterns of plasticity in both phenotypic traits and DNA methylation in response to water regime (Figure 3; Williams et al. 2025). In contrast, the rare apomict Kentucky gladecress displayed no phenotypic plasticity or plasticity in DNA methylation (Fig. 3). These differences among species suggest a possible relationship between geographic range size and plasticity in phenotypic and DNA methylation (Williams et al. 2025). Our results suggest that variation in DNA methylation may promote the persistence of genetically depauperate threatened plants, highlighting its potential as a novel conservation target to reduce extinction risk (Williams et al. 2025).

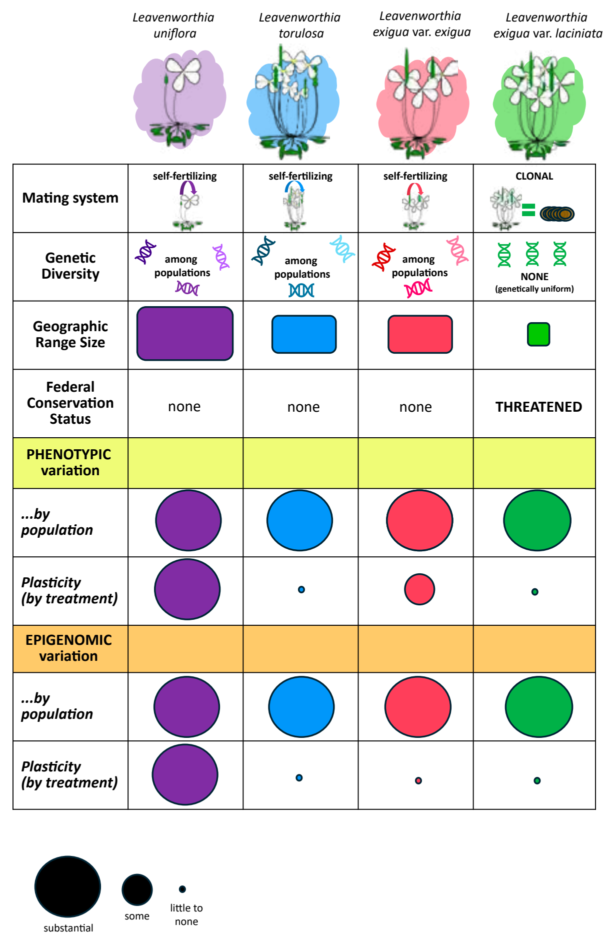


Figure 3. Results of analyses of phenotypic and epigenomic variation in four species of Leavenworthia that vary in mating system, genetic structure, geographic range size, and conservation status. Dots of various sizes indicate the extent to which each species exhibited phenotypic or epigenomic variation by population or by treatment

Conclusions

In summary, the reduced cost of high-throughput DNA sequencing and the corresponding advances in library preparation and analytical techniques now provide us with unprecedented insights into endangered species that greatly facilitate conservation efforts. Now, we can generate the amount of data for a species of conservation concern that was previously only possible for model species. The data can be used for standard population genetics and phylogenetics; but they can also be used to estimate genetic load, runs of homozygosity, the genomic basis of local adaptation and phenotypic traits. It is also providing insights into the mechanisms that may enable species with low genetic variation to respond to evirnomental stress, namely epigenomic variation. The technological advances that have been made in genomics have revolutionized the field of conservation genetics, providing us with important information that greatly expands our knowledge and ability to conserve threatened and endangered species.

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Mike Leahy Receives Natural Areas Association Carl N. Becker Stewardship Award

By Nate Muenks

Congratulations to Mike Leahy, Missouri Department of Conservation (MDC) Natural Community Ecologist, who recently received the 2025 Natural Areas Association's Carl N. Becker Stewardship Award. The Carl N. Becker Stewardship Award recognizes excellence and achievement in managing reserves, parks, wilderness, and other protected areas. It is given in memory of Carl N. Becker, former Natural Areas Association (NAA) president and an inspirational leader in conservation.

Leahy was nominated by his colleagues for his 31 years working for state conservation agencies in Indiana, Virginia, and Missouri primarily in the field of native biodiversity conservation. He has also devoted much personal time to understanding, communicating about, and protecting natural areas and natural communities. Since 2006 he has served as MDC's coordinator for the Missouri Natural Areas Program. During that time he has worked with MDC staff, other governmental agencies, and private partners from multiple natural resource disciplines to inventory, designate, restore, and manage a system of Missouri Natural Areas. This has included overseeing the designation of 15 new Missouri Natural Areas on MDC lands (totaling over 10,000 acres) and 11 additions to existing ones.

He served as a NAA board member for eight years (2012–2020) and continues to serve as the Chair of the NAA State Natural Areas Program Committee. Leahy was a leader in hosting NAA conferences in Missouri in 2000 and 2010. Leahy has published several peer-reviewed publications and contributed to general audience works throughout his career, including authoring the popular MDC guidebook, Discover Missouri Natural Areas, A Guide to Fifty Great Places. In recent years he has worked with colleagues at MDC, the U.S. Forest Service, and the University of Missouri–Columbia on the development and implementation of natural community health index (CHI) surveys that are rapid assessment tools for ecological integrity monitoring.

Missouri Department of Conservation photo

Figure 1. Mike Leahy in a wet bottomland prairie natural community explaining its ecology during a staff training for Conservation Department biologists.

Leahy continues to serve the inter-agency Missouri Natural Areas Committee and enjoys giving presentations and training for MDC staff, Missouri Master Naturalists, and other conservation groups on Missouri's natural communities. He also serves as the lead ecologist for the Missouri Natural Heritage Database and as a technical advisor to the L-A-D Foundation.

Nate Muenks is the co-Chair of the Missouri Natural Areas Committee

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New Natural Areas in 2025

By Mike Leahy

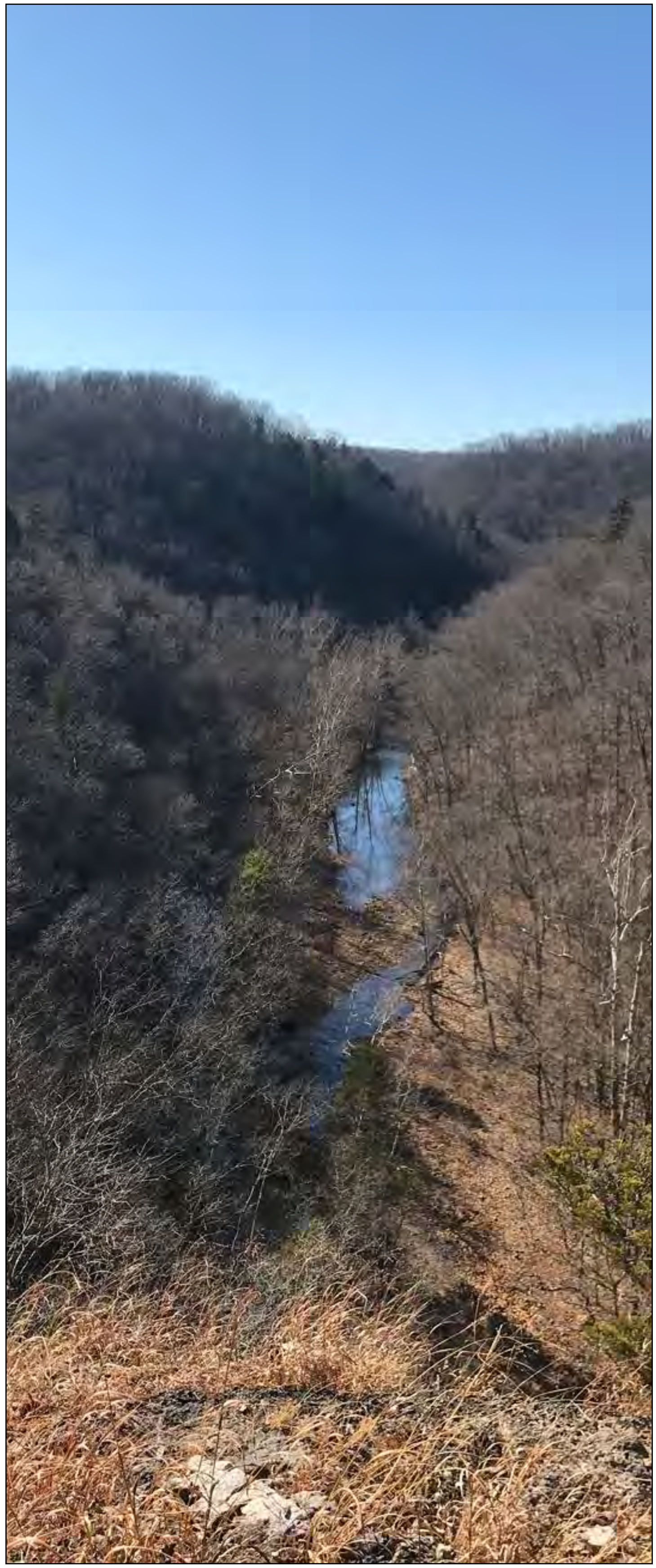
In 2025, two natural areas were formally added to the natural areas system and one is pending approval from the directors of the Missouri Department of Conservation and the Missouri Department of Natural Resources.

Leatherwood Creek Natural Area

This 1,440 acre Missouri Natural Area in Shannon County was formally designated in April 2025. This site is owned and managed by the L-A-D Foundation. The natural history value of Leatherwood Creek valley has been known for a long time, beginning with Leo Drey, the founder of Pioneer Forest. Drey recognized the value of this site for biodiversity conservation and the area was the first 'forest reserve' designated on Pioneer Forest. (Figure 1). This site features a high-quality spring-fed headwater creek Ozark valley with important karst, aquatic and terrestrial natural communities that support 17 Species of Conservation Concern (SOCC), including one new to the state. 587 native plant species have been documented on the area. High quality Ozark fens, dry-mesic and mesic forest types, protected dolomite bluffs, 30 caves, a significant natural arch, and interesting gravel wash communities occur here.

Steyermark Sand Prairie

This 22 acre site in Clark County is part of Frost Island CA (MDC). The committee visited the site in May 2024 and at its October 8, 2025, meeting the committee recommended the site for natural area designation. Steyermark Sand Prairie NA



Missouri Department of Conservation photo by Mike Leahy

Figure 1. Leatherwood Creek Natural Area's steeply incised valleys allowed for the development of multiple natural communities.

was formally designated in December, 2025. Sand prairie is one of the rarest natural community types in Missouri. The site supports 5 plant SOCCs, Bull Snakes, Eastern Tiger Salamanders, and a SOCC bumblebee. There are no sand prairies currently in the Missouri Natural Areas System. Ongoing restoration efforts by MDC staff on the area and conversion of surrounding croplands to native prairie plantings have greatly increased the conservation value of this property. Julian Steyermark, the famous Missouri botanist, visited this site for plant collections over 70 years ago and is the namesake for this new natural area. (Figure 2)

Photo by Mike Leahy

Figure 2. The Steyermark Sand Prairie Natural Area harbors unique plant species like this fringed puccoon *(Lithospermum incisum).*

Ball Mill Resurgence Natural Area

Currently this natural area is 19 acres and was designated in 1979 for its geologic features. The site is owned by the L-A-D Foundation and managed by MDC. The Foundation along with Scott House (Cave Research Foundation) recommended a 65 acre addition to the original natural area for more recent acquisitions of geologic features. The committee visited the site with a variety of MDC and L-A-D staff on October 7 (Figure 3). On October 8 at its meeting the committee recommended these 65 acres be added to the original designated natural area. It is pending final approval from the directors of MDC and DNR. The expansion, like the original natural area, protects significant geologic features. The expansion adds a number of karst features including resurgences and springs. Blue Spring is the largest and is the outlet for the Berome Moore Cave, the second longest cave in Missouri (18 miles). This cave system also supports the federally listed Grotto Sculpin. The sculpin also occurs periodically in this spring branch.

Photo by Allison Vaughn

Figure 3. Former Department of Natural Resources (DNR) MoNAC representative and current L-A-D Foundation Board Member John Karel stands next to a plaque honoring the late geologist and former DNR MoNAC representative Jerry Vineyard who studied and nominated the original 19 acres of Ball Mill Resurgence Natural Area.

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IN MEMORIAM:

Tom Aley, 1938–2025

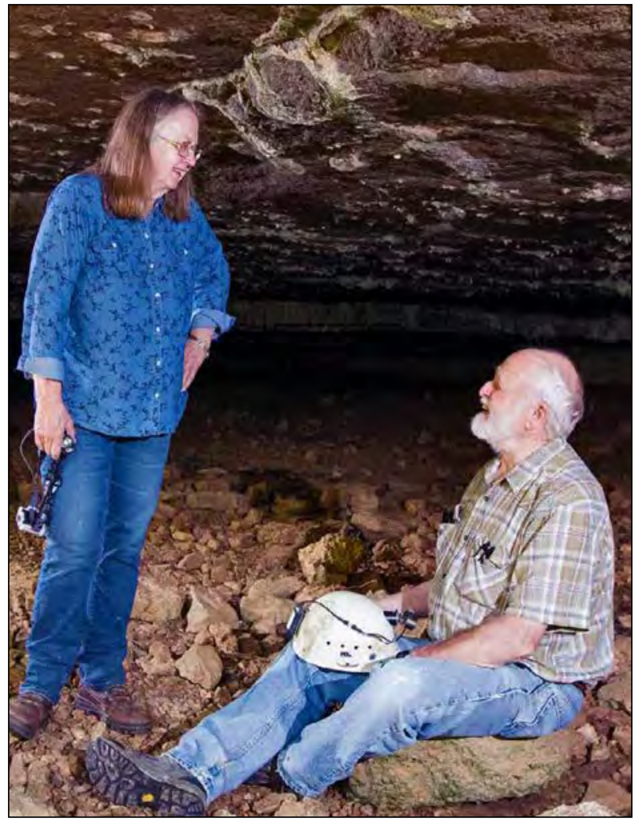
By Dave Woods

Tom Aley, widely known hydrogeologist, speleologist, and founder of both the Ozark Underground Laboratory (OUL) and the Tumbling Creek Cave Foundation (TCCF), died on October 20th after a two-year battle with pancreatic cancer. He is survived by wife Cathy, son Dave, and daughter Anna.

Tom received BS (1960) and MS (1962) degrees in forestry from the University of California at Berkeley. Additional education focused on hydrology and geology was at UC Berkeley (1963–1964); University of Arizona in Tucson (1963–1964); and at Southern Illinois University in Carbondale (1972–1973). Tom was licensed as a Professional Geologist in Missouri, Arkansas, Kentucky, and Alabama and held national certification as a Professional Hydrogeologist and as a Certified Forester.

Tom was a pioneer in cave and karst management, conservation, and education for the past 60 years. In 1965, he purchased land above a cave system (Tumbling Creek Cave) in eastern Taney County, Missouri for the sole purpose of establishing the OUL. For nearly six decades, Tom worked on hydrogeological issues that affected caves and karst systems across the globe. Much of his innovative work has become standard practice in the field of groundwater tracing and his services have been contracted by agencies, companies, and non-government organizations across the globe. Tom literally "wrote the book" on groundwater dye tracing, authoring *Practical Groundwater Tracing with Fluorescent Dyes* in 2025 as an open-source, online book as part of the Groundwater Project book series.

In addition to his professional successes, Tom and his wife Cathy dedicated their time and income protecting cave and karst features on their own property. Little was known about Tumbling Creek Cave prior to Tom purchasing the property, but since that time Tom and Cathy discovered that they owned one of



Missouri Department of Conservation photo by David Stonner

Figure 1. Tom and Cathy Aley exploring Tumbling Creek Cave. Tom lived life with a purpose. Together, Tom and Cathy have dedicated their lives and livelihoods to educate people about karst and to safeguard one of Missouri's most amazing natural features.

Missouri's most significant caves. With approximately 130 species currently documented from the cave including four federally endangered species, Tumbling Creek Cave became recognized as the most biodiverse North American cave west of the Mississippi River and was designated a National Natural Landmark by the Department of the Interior in 1981. The Aleys have conducted over 100 groundwater traces to delineate the cave's nine square mile recharge area, linking important surface features to the health of the cave.

Within the cave itself, Tom went to great lengths to protect the geologic features, water quality, and biota that call the cave home. The cave is a maternity site for roughly 40,000 federally endangered Grey Bats. Tom worked with the Missouri Department of Conservation (MDC), the U.S. Fish and Wildlife Service (USFWS), and the American Cave Conservation

Association in 2004 to build a bat-friendly cave gate on the natural entrance to protect this sensitive habitat from trespass and vandalism. In partnership with the USFWS, Tom installed a water quality monitoring station in the cave in 2002 to measure water quality parameters in the cave stream. Much of the conservation successes at Tumbling Creek Cave have been centered around protection of the federally endangered Tumbling Creek Cavesnail (*Antrobia culveri*), an aquatic endemic in the cave. The Aleys have been the driving force behind these efforts through their involvement in the recovery team, work with universities and researchers, and a huge investment of their time and the time of their staff. In a cooperative effort with MDC to protect the endangered cavesnail, OUL staff have been trapping and removing invasive crayfish in the cave on a weekly basis since 2013. The Aleys also constructed an artificial cavesnail propagation system within the cave. In the event of an environmental disaster on the roads in the cave recharge area, cavesnails can quickly be moved to the closed system to avoid a major mortality event. Tom also worked with the Springfield Plateau Grotto of the National Speleological Society to restore areas of the cave that had been vandalized with graffiti or speleothems that had been broken or covered in mud deposits.

Over the last half century, the Aleys have invested much of their personal wealth into acquiring and restoring almost 3,500 acres of land in and around the cave's recharge area. These efforts included restoration of over 13,000 feet of erosion gullies and 1,600 feet of eroding stream banks, hand-planting about 75,000 trees in riparian corridors, restoration of glades and grasslands, and removing over 100 tons of refuse and 100 gallons of hazardous liquids from over 30 dumps and sinkholes on their land and neighboring properties in the cave's recharge area. In one instance, Tom offered to clean up a dump on a neighboring six-acre tract of land. When the landowner declined the assistance, Tom instead bought the property and cleaned up the dump. In 2004, the Aleys established the TCCF to ensure the protection of the cave and associated lands into the future. Tom and Cathy have donated approximately 1,000 acres of land to the Foundation with plans that all their remaining lands be donated to the Foundation upon their passing.

Despite his many contributions to the fields of cave and groundwater research, and the countless conservation practices he implemented on lands within the Tumbling Creek Cave recharge area, Tom would probably say that his most important accomplishment had been his efforts to educate the public about caves and karst. Beginning in the 1960's, the OUL began providing field trips for students and professional groups in Tumbling Creek Cave. To date, the OUL has conducted over 2,000 educational field trips at the cave. These day-long trips and professional short courses showcase the direct links between land use on the surface and the health of caves and groundwater. The Ozark Underground Lab has also hosted dozens of graduate students who have conducted research in and around the cave. Tom and Cathy have created a tremendously impressive educational experience and field station to promote karst conservation and land stewardship.

The OUL and TCCF will continue operation. Well before his passing, Tom had the foresight to implement a succession plan to ensure that his legacy will live on. Staff of both organizations are committed to Tom's vision more than ever and will continue efforts to lead karst research, conservation, and management well into the future. For more information, visit the websites of the OUL[1] and TCCF[2].

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1 https://ozarkundergroundlab.com

2 http://tumblingcreekcave.org