An Ecological Evaluation of the Tomahawk Sinkholes and Pine Barrens

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Cover Photo: A sinkhole with barrens vegetation in the foreground. Photo by Jesse M. Lincoln, 2023. All pictures by Jesse M. Lincoln unless otherwise noted.

Land Acknowledgement: We collectively acknowledge that Michigan State University occupies the ancestral, traditional, and contemporary Lands of the Anishinaabeg – Three Fires Confederacy of Ojibwe, Odawa, and Potawatomi peoples. In particular, the University resides on Land ceded in the 1819 Treaty of Saginaw. We recognize, support, and advocate for the sovereignty of Michigan's twelve federally-recognized Indian nations, for historic Indigenous communities in Michigan, for Indigenous individuals and communities who live here now, and for those who were forcibly removed from their Homelands. By offering this Land Acknowledgement, we affirm Indigenous sovereignty and will work to hold Michigan State University more accountable to the needs of American Indian and Indigenous peoples.

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Introduction

Pine barrens are one of several fire-dependent natural community types in Michigan. In the past, fires ignited by humans and lightning frequently spread over large areas of the landscape, helping to reduce establishment by trees and shrubs and maintaining the open structure and composition of these fire-dependent communities. European colonization has caused fire suppression and barrens not cleared for development have converted to closed-canopy forests dominated by shade-tolerant species. The loss of barrens to forest has resulted in significant reductions in species and habitat diversity and the restoration of barrens is a conservation priority (Cohen et al. 2021).

There are over 4 million acres of State Forest across the Upper Peninsula and Northern Lower Peninsula of Michigan. State Forest is jointly managed by the Forest Resources Division (FRD) and Wildlife Division (WLD) of the Michigan Department of Natural Resources (DNR) for long-term forest health, sustainable forest products, wildlife habitat, recreational opportunities, and ecosystem services. The FRD and WLD are responsible for assuring that management activities do not harm threatened and endangered species, and through dual forest certification, the DNR maintains a network of Ecological Reference Areas composed of high-quality and representative natural communities. Michigan Natural Features Inventory (MNFI) is Michigan's natural heritage program and maintains a geospatial database of populations of rare and declining plants and animals and benchmark ecosystems. The DNR commissioned MNFI to evaluate the condition and management needs of the Tomahawk Barrens that occur along the slopes of a series of sinkholes in Presque Isle County in Michigan's Northeastern Lower Peninsula.

The Tomahawk Barrens and sinkholes occur within the Atlanta State Forest Management Unit (Compartment 54120). The site was recommended as a potential Biodiversity Stewardship Area by DNR staff and first described by MNFI scientists in 2011. The DNR has shown increasing interest in returning fire to high quality barrens habitats for a range of conservation goals. Additionally, since the initial survey, the sinkholes have been impacted by erosion along their edges and the surrounding area

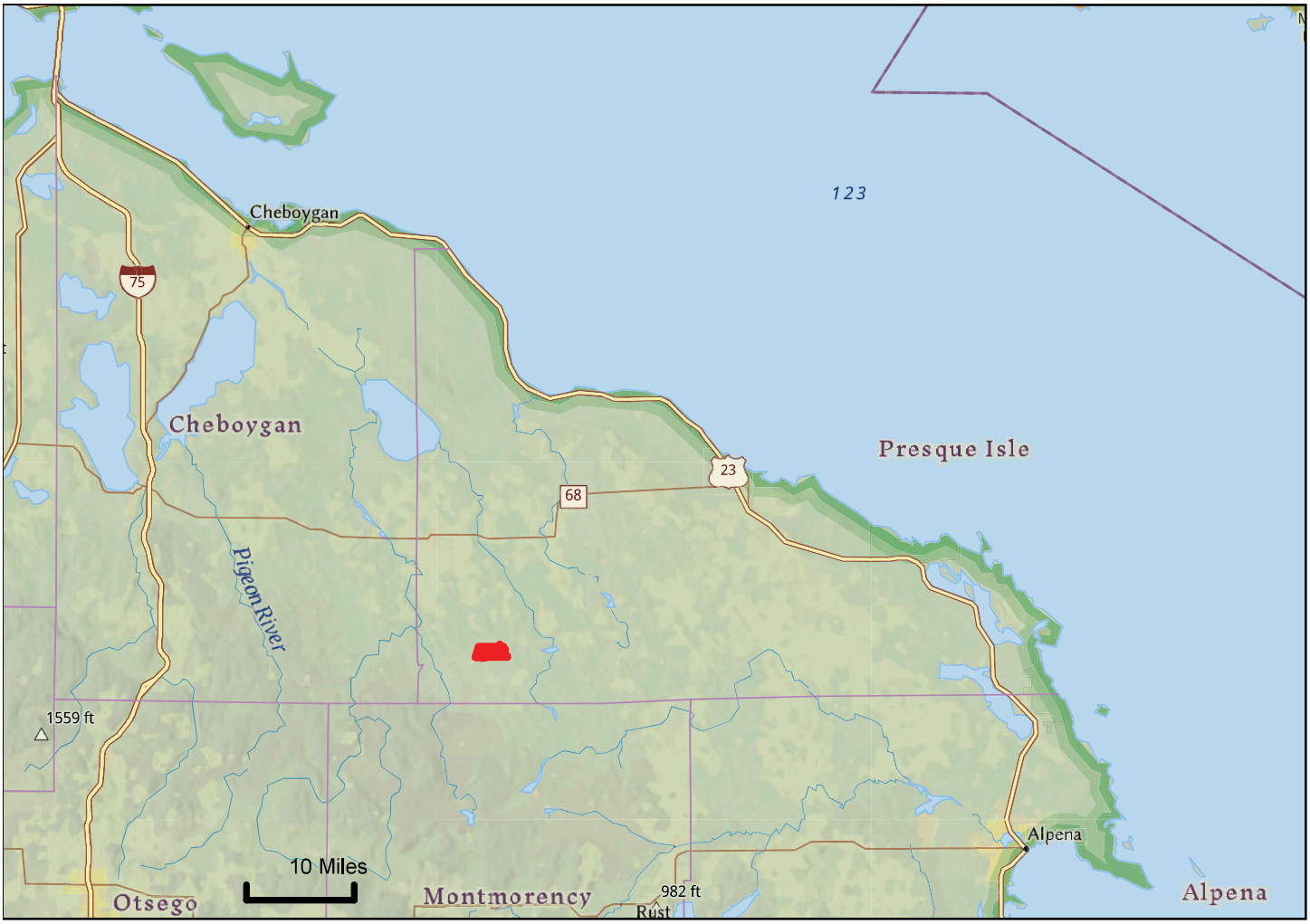


Figure 1. Location of Tomahawk Sinkholes and Pine Barrens (highlighted in red) in the Northern Lower Peninsula. The site occurs within the Atlanta State Forest Management Unit.

has been impacted by forestry activities. This report summarizes the 2023 field surveys and ecological evaluation of Tomahawk Sinkholes and Pine Barrens by MNFI conservation scientists and provides management recommendations.

Natural Community Description and Landscape Context

A natural community is defined as an assemblage of interacting plants, animals, and other organisms that repeatedly occurs under similar environmental conditions across the landscape. They are predominantly structured by natural processes rather than modern anthropogenic disturbances such as timber harvest, alterations to hydrology, and fire suppression (Kost et al. 2007, Cohen et al. 2015). Historically, Indigenous Peoples were an integral part of natural communities across the Great Lakes region with many natural community types being maintained by native land tending practices such as cultural burning, wildlife management, and plant harvesting, seeding, and planting (Kimmerer and Lake 2001, Stewart 2009).

In the Great Lakes region, ancient limestone deposits formed during the Devonian era (400 mya) have eroded and caused the formation of sinkholes. These karst features form from the underground dissolution of limestone, dolomite, or gypsum, often along faults or cracks in the bedrock. This results in the creation of an underground drainage system rather than typical surface streams. As the dissolution of the underlying bedrock continues, it collapses in some locations and forms sinkholes, some of which seasonally or permanently flood to form lakes or ponds (Figure 2). Sinkholes occur in a limited areas around the state and there are only five documented occurrences in Michigan, predominantly in the northeastern Lower Peninsula and eastern Upper Peninsula.

The Tomahawk Sinkholes are primarily situated along the Shoepac/Rainey Fault which is a crack in the bedrock that runs east to west. Locally, there is about 100 ft of glacial drift over the Detroit River Group limestone bedrock below. Soils are approximately 20 ft of well-drained sand over clay, allowing for the extremely steep conditions of the sinkholes. The varied clay composition of the drift causes some sinkholes to be dry, despite some of the sinkhole bottoms being 90 ft below Shoepac Lake. These unique karst formations are critically imperiled and feature unusual concentrations of plant diversity, most notably the remnant pine barrens that occur on the south-facing slopes of several of the local sinkholes (Black 1995).

Pine barrens are fire-dependent, savanna communities with a canopy cover between 5 and 60%. Pine barrens typically occur on droughty, sandy soils, and are often dominated by jack pine with red

The south-facing slopes of the sinkholes feature concentrations of barrens vegetation. Picture from Sinkhole 7.

and white pine as important canopy associates (Albert 1989). The herbaceous layer consists predominantly of graminoids and contains plant species associated with both prairie and forest. Historically, barrens likely occurred across the landscape, particularly in areas where Indigenous cultural fires were most frequent and where features on the landscape promoted open conditions. These landscape features include depressions acting as frost pockets, drought-prone deep sands, and south-facing slopes along lakes and rivers.

Surveyors from the General Land Office (GLO) took detailed notes of the Michigan landscape prior to widespread logging. Surveyors recorded information on tree species composition, tree size, and general condition of the lands. Based on those notes, we know that nearly 270,000 acres of pine barrens were present in Michigan in the 1800s (Comer et al. 1995; Figures 3 and 4). About 210,000 acres were distributed in the Lower Peninsula of Michigan. Most of this acreage was concentrated in Crawford County (55,000 acres), Iosco County (33,000 acres), and Oscoda County (28,000 acres). In the Upper Peninsula, pine barrens were mostly concentrated on the Raco Plains of Chippewa County and the Baraga Plains in Baraga County. Since European expansion, most of these systems have been lost to agriculture, converted to forest because of

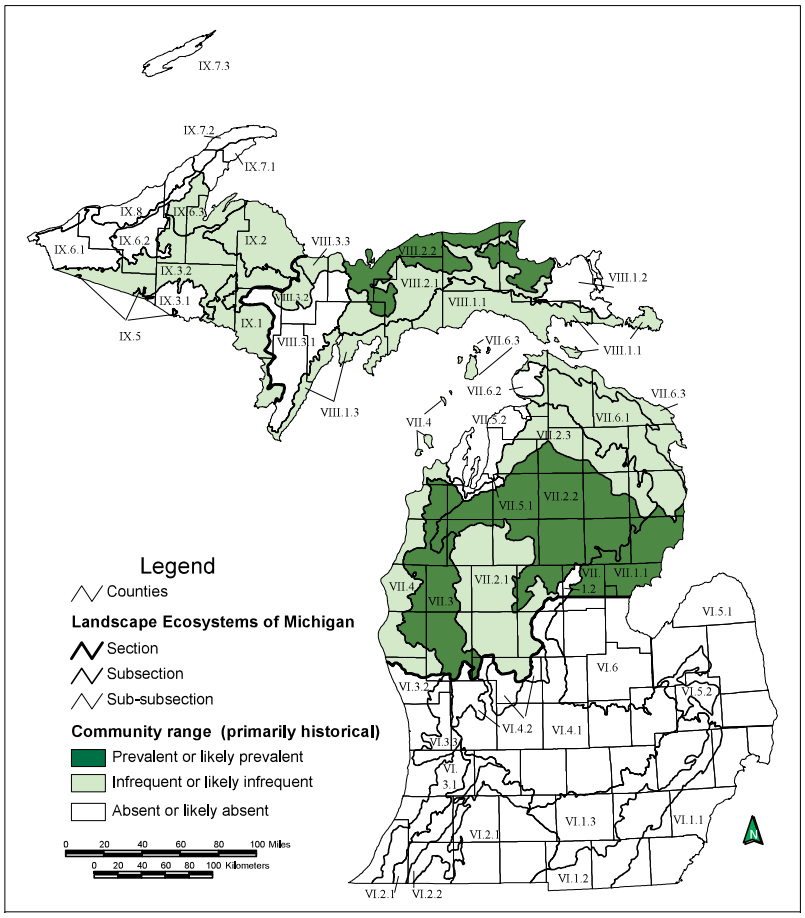


Figure 3. Historical distribution of pine barrens in Michigan (Albert et al. 2008).

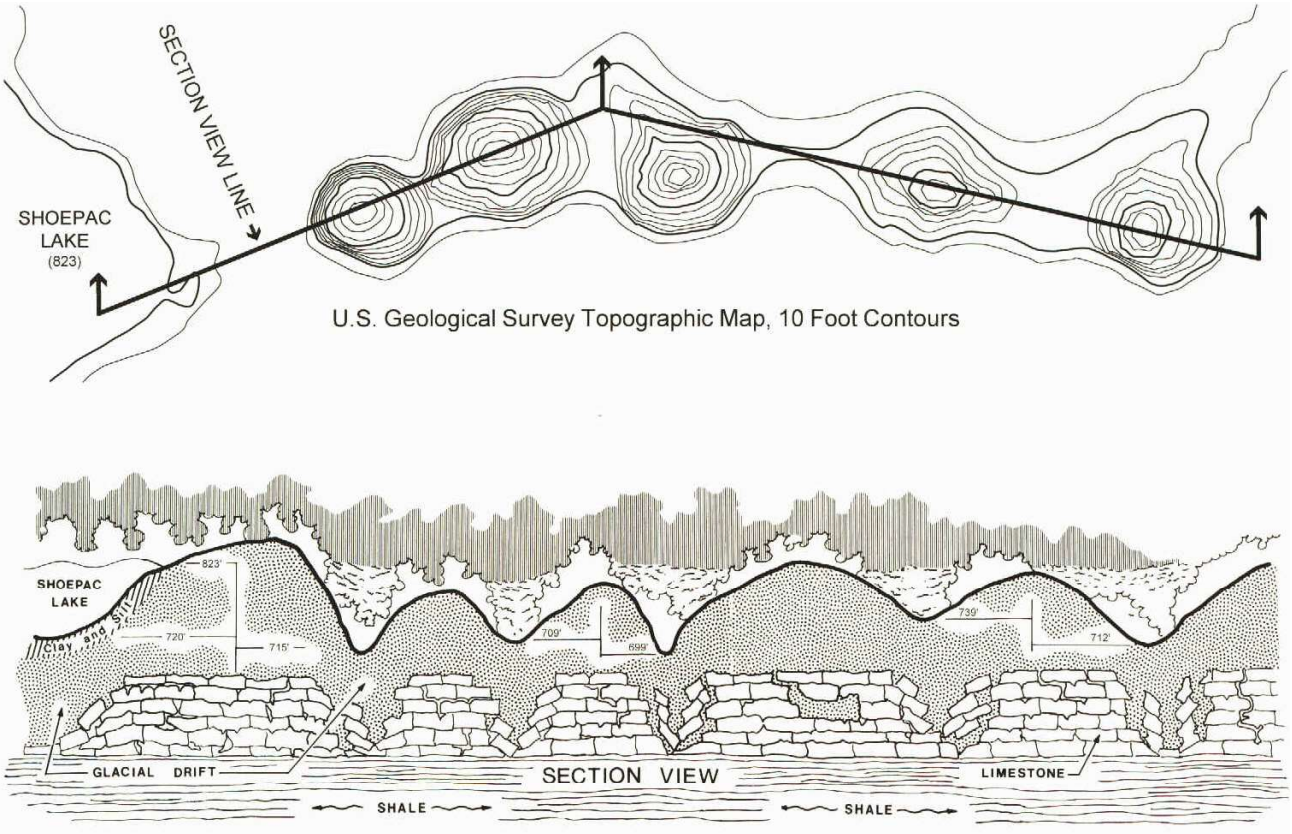


Figure 2. Cross section of the Tomahawk Sinkholes. From left to right, Sinkholes 8 through 4 (from unknown United States Geological Survey report, accessed online May, 2024).

fire suppression, or developed as cities and towns (Comer et al. 1995, Comer 1996, Chapman and Brewer 2008).
The Tomahawk Sinkhole area was first described in September of 1851 by GLO surveyor George H. Cannon. He described a landscape with “sandy soil – timber spruce & yellow pine – mostly burnt." Jack pine was often called “spruce pine” and red pine was referred to as “yellow pine” in notes from the first surveyors. Cannon also described a “deep circular basin" with a depth of 150 ft.

Barrens openings were relatively small and occasionally missed in the GLO surveys as a result of the coarse scale of the historic mapping efforts and the focus on timber resources. Despite no mention of barrens or prairie in the GLO notes for the area surrounding Tomahawk Sinkholes, the persistence of areas supporting barrens vegetation on the modern landscape allows us to assume there was barrens vegetation on the landscape in the 1850s. This would have occurred within a shifting mosaic of a sparsely canopied pine forest as described in Cannon’s notes. Today, local concentrations of barrens species are primarily restricted to the steep south-facing slopes of the sinkholes where factors such as drought or frost have prevented conversion to closed-canopy forest in the absence of fire.

This is one of five documented Sinkhole sites in Michigan and there are currently 4,012 acres of documented high-quality pine barrens in the state – approximately 1.5% of historical extent. Of the 25 documented barrens in the state, only 4 are of good to excellent viability with the remainder qualifying as fair to poor viability. There are likely additional areas of recoverable pine barrens that have not been documented. However, the fragmented and degraded status of most of Michigan’s documented pine barrens has resulted in the drastic decline of species associated with barrens habitats. Therefore, conservation and restoration of these natural communities is paramount to protecting rare biodiversity and preventing additional taxa from becoming rare or extirpated (Kost et al. 2007 and Cohen et al. 2015). The co-occurrence of sinkholes and pine barrens makes the Tomahawk Sinkhole site unique in the state and an important conservation priority for the DNR.

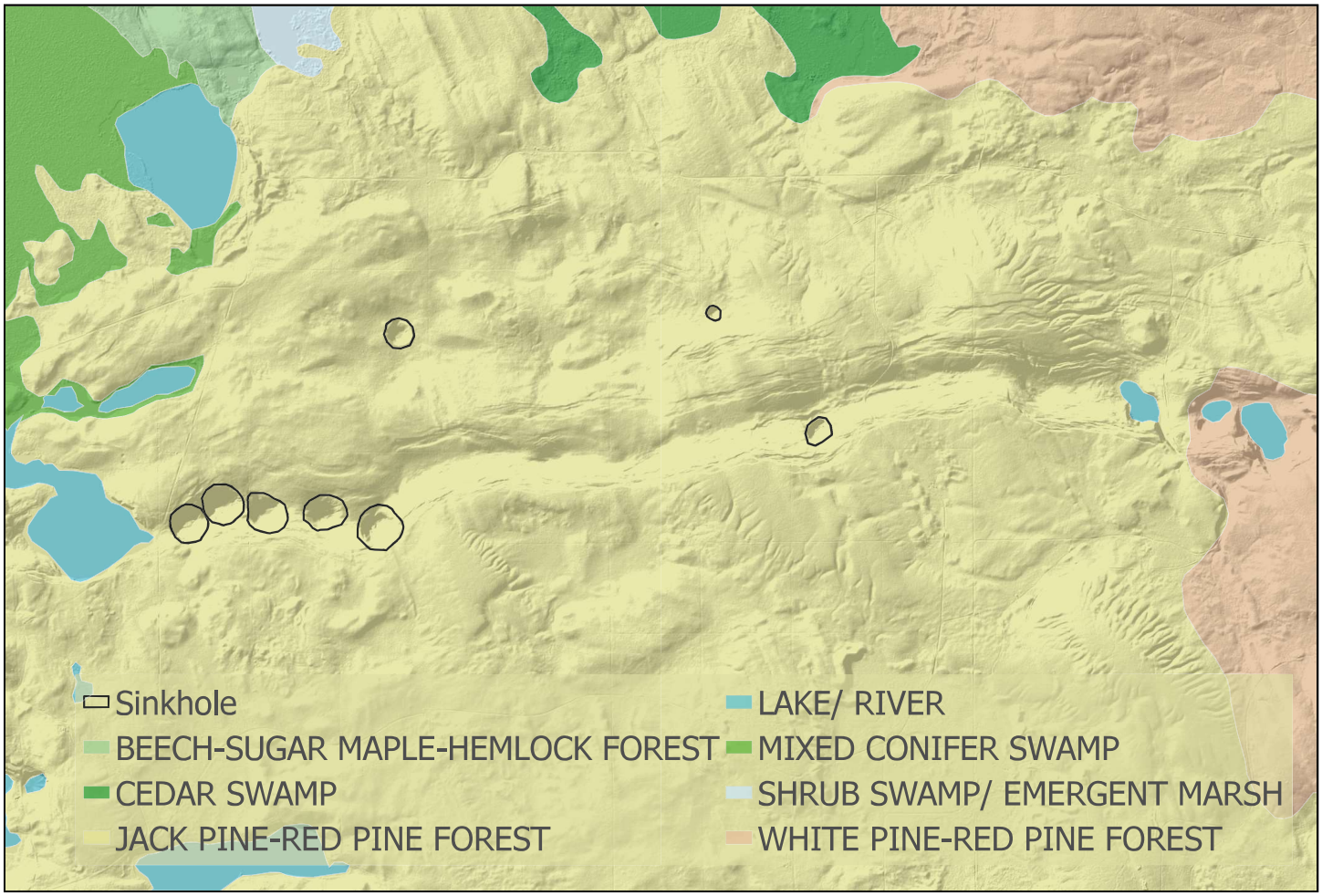
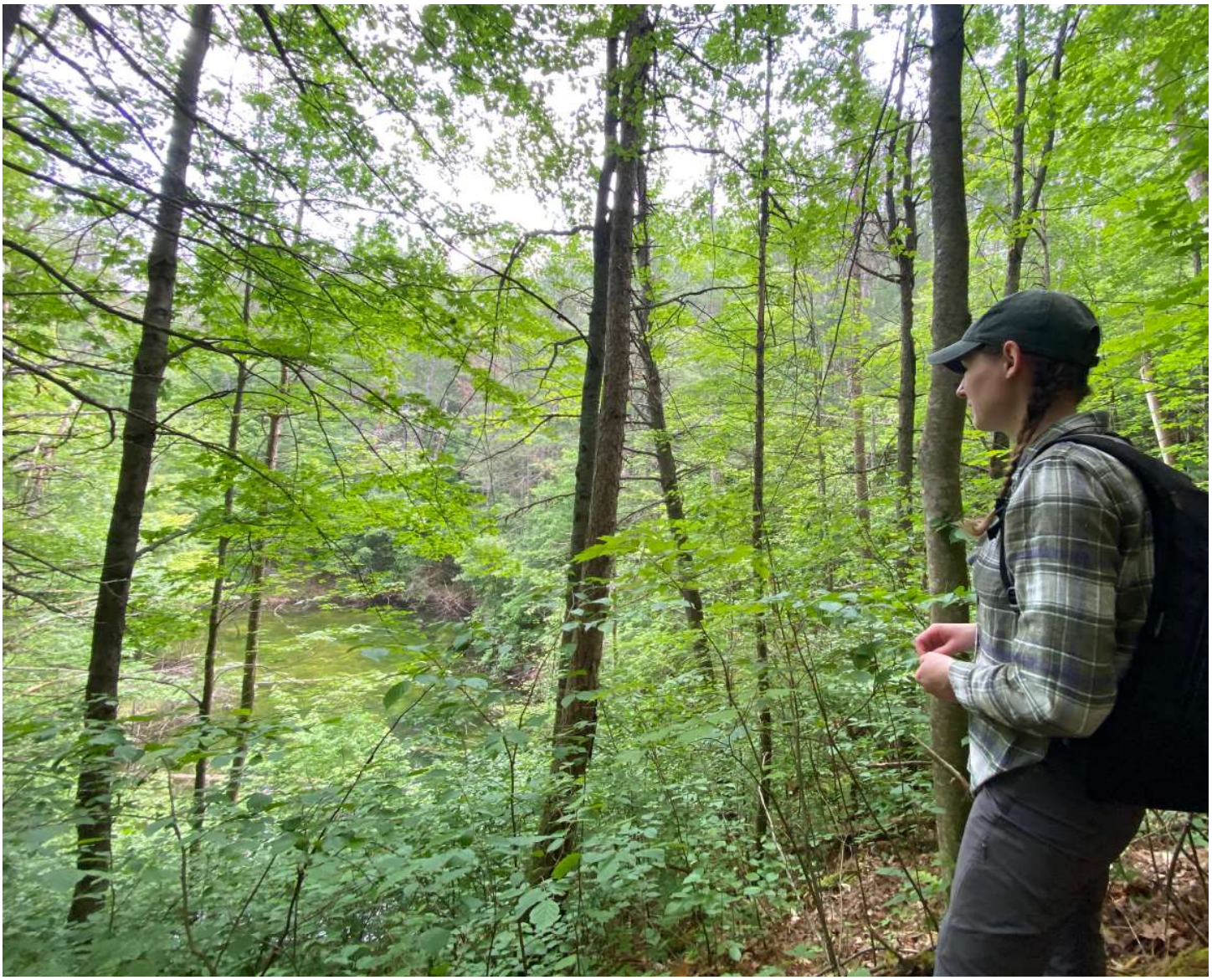


Figure 4. A Digital Elevation Model showing the topography of the area around the sinkholes. Notes from the General Land Office surveys were transcribed to develop the circa 1800 vegetation map (Comer et al. 1995), which overlays the elevation model. While GLO notes fail to describe barrens vegetation in the area, the concentration of barrens vegetation allows us to assume there were some areas of barrens vegetation on the landscape at the time which would have occurred within a shifting mosaic of pine forest.

Methods

Ecological evaluations are important for facilitating site-level decisions about prioritizing management objectives to conserve native biodiversity, evaluating the success of restoration actions, and informing landscape-level planning efforts. Throughout this report, a documented occurrence of a high-quality natural community at a specific location is referred to as an “element occurrence” (EO). MNFI methodology considers three factors to assess a natural community’s ecological integrity or quality: size, landscape context, and condition (Faber-Langendoen et al. 2008, 2015). If a site meets defined requirements for these three criteria (MNFI 1988), it is categorized as a high-quality example of that specific natural community type, entered into MNFI’s database as an EO, and given a rank of A (excellent) to D (poor) based on how well it meets the above criteria.

Field surveys of the Tomahawk Sinkholes and Pine Barrens and surrounding stands were conducted on June 12, 13, and 14 of 2023. Methods employed during this survey followed the methodology developed during the initial evaluation of Ecological Reference Areas on State Forest land by MNFI ecologists (Cohen et al. 2008; Cohen et al. 2009). We used aerial photographic interpretation and Geographic Information Systems (GIS) to navigate and guide qualitative meander surveys to assess boundaries of the natural communities, landscape context, and other abiotic factors. Vegetative composition, community structure, tree size and age, populations of rare plants, and soils were all assessed while evaluating overall rank of the sinkholes and pine barrens. We carefully documented threats to the site to develop management recommendations that will



Wildlife Biologist Angela Kujawa of the Michigan Department of Natural Resources surveying the dry-mesic northern forest in Sinkhole 3.

serve to protect the ecological integrity of the site and populations of rare species therein.

Floristic data from the surveys were compiled into the Universal Floristic Quality Assessment Calculator (Reznicek et al. 2014, Freyman et al. 2016) to determine the Floristic Quality Index (FQI) for Tomahawk Pine Barrens. The floristic quality assessment is derived from a mean coefficient of conservatism and floristic quality index. Each native species is assigned a coefficient of conservatism (C value), a value of 0 to 10 based on probability of its occurrence in a natural versus degraded habitat. Species restricted to a specialized or undisturbed habitat are assigned a value of 10, implying the species has extremely strong fidelity to a specific habitat. Native species that are not particular or indicative of natural conditions are assigned a low value of 0 or 1. The coefficient of conservatism is determined by experts on the flora of a region, and so may vary for a given plant species from region to region. From the total list of plant species for an area, a mean C value is calculated and then multiplied by the square root of the total number of plant species to calculate the FQI. Michigan sites with an FQI of 35 or greater possess sufficient conservatism and richness that they are considered floristically important from a statewide perspective (Herman et al. 2001). FQI scores greater than 50 indicate exceptional sites with extremely high conservation value (Herman et al. 2001). Mean C values may represent a less biased indicator of relative conservation value and are provided with conservation metrics in the appendix (Matthews et al. 2005; Slaughter et al. 2015). Species lists are provided in the Appendices.

Detailed species lists were developed for each community type. Careful attention was given to ensure accuracy of species identification. Poa species were especially prevalent, including native and non-native species. Pictured above is *Poa saltuensis*, a native bluegrass.

Results

There are eight separate sinkholes and the vegetation in each is highly variable. To facilitate discussion and direct management objectives, the sinkholes were numbered, with the northwestern sinkhole being 1 and then proceeding clockwise such that the northeastern most sinkhole is 2, the southeastern sinkhole is 3 and then the remaining cluster of five sinkholes are in the southwest (Figure 5). Sinkholes four through eight form the primary cluster along a 1000 m line. Sinkhole three occurs 2000 m to the east of the cluster of five sinkholes and along the same line known as the Shoepac/Rainey Fault. The other two are much more remote, occurring about 700 m to the north of the fault line. While the separation distance would typically preclude EOs from being mapped together, the unique nature of the sinkholes caused us to treat them as a single occurrence.

Sinkholes 4 through 8 were documented in 2011 and Sinkholes 1 through 3 were added in 2023. The extent of the pine barrens was refined and expanded from 7.0 to 15.3 acres with two additional areas being documented on Sinkhole 1 and 2. An occurrence of a dry-mesic northern forest was documented during the 2023 surveys. The very small forest occurs around Sinkhole 3 and the southern slopes of Sinkholes 6, 7, and 8. Descriptions of the three natural communities follow (Figure 7).

Description of the Tomahawk Sinkholes

The sinkholes exist in a matrix of dry northern forest, featuring a prevalence of jack pine, red pine, northern pin oak, white pine, and infrequent white oak. The ridge to the south of the sinkholes features red oak and bigtooth aspen and appears much more mesic than the predominant areas of outwash sands on the landscape. There are many repeating floristic components within the sinkholes but the composition of each sinkhole is highly varied and unique. They generally feature dry-mesic northern forest on the north-facing portion of the sinkholes which tend to be the steepest. Pine barrens and dry northern

Table 1. Natural communities documented at the Tomahawk Sinkhole site. EO rank abbreviations are as follows: B, good estimated viability; C, fair estimated viability.

EOID	Site Name	Community Type	Stands	First Survey	Last Survey	Size (Acres)	Overall Rank	Total FQI	Native Mean C
18854	Tomahawk Sinkholes (Update)	Sinkhole	45, 78, 80, 81, 82, 104, 113	8.30.2011	6.17.2023	38.0	B		
18852	Tomahawk Barrens (Update)	Pine Barrens	45, 78, 80, 81, 82, 104	8.30.2011	6.17.2023	15.3	C	42.0	4.5
27361	Tomahawk Forest (New)	Dry-mesic Northern Forest	78, 82, 113	6.17.2023	6.17.2023	15.1	C	31.4	4.2

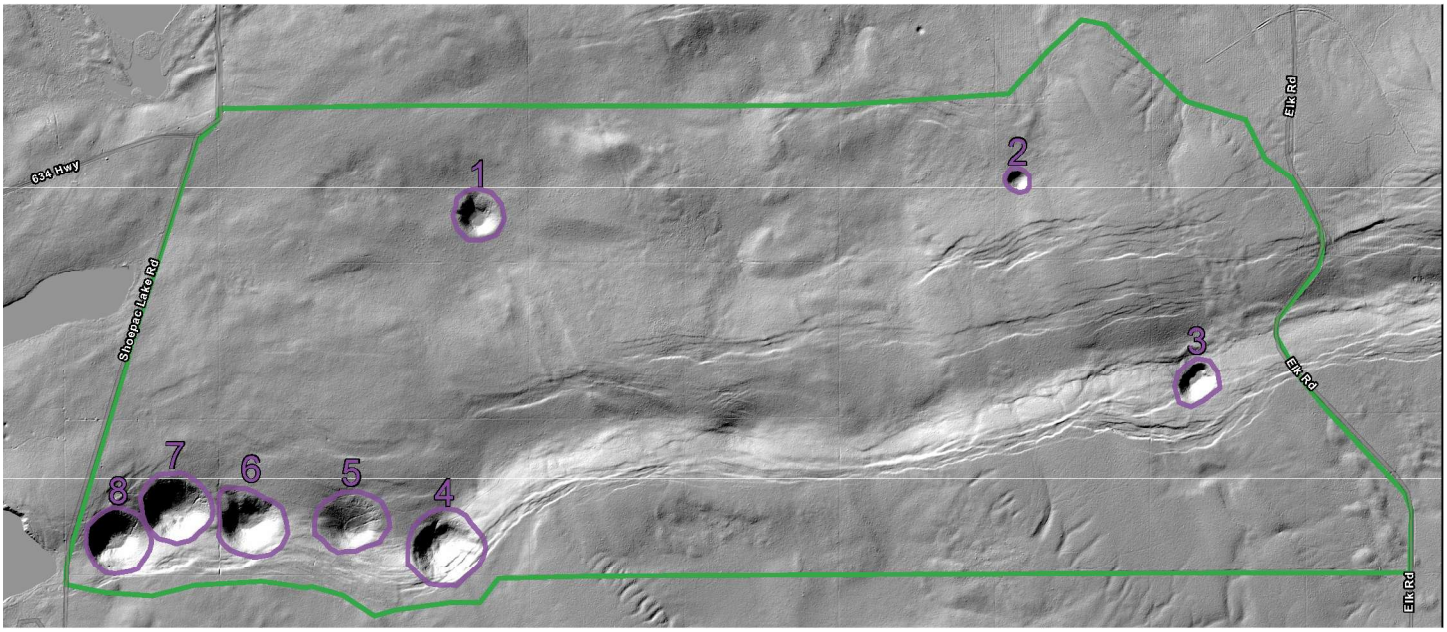


Figure 5. Digital elevation model of the Tomahawk Sinkholes. Sinkholes are numbered 1 through 8 to facilitate discussion of the site.

forest occur on the south-facing portion of the sinkholes where the southerly aspect exacerbates the droughty conditions of the deep sands. The southern slopes hold snow for much later in the year and the sinkholes serve as frost pockets that experience growing season frosts. The aspect, edaphic features, and other factors cause substantial variability in moisture and temperature and the sinkholes provide microclimates with much cooler temperatures than the surrounding landscape, facilitating concentrations of plant diversity on an otherwise fairly low diversity landscape.

The sinkholes range in size with Sinkhole 2 the smallest at 40 ft deep and about 150 ft across

Table 2. Elevation profiles of Tomahawk Sinkholes.

Sinkhole #	Minimum elevation	Maximum elevation	Depth (ft)
1	763.8	815.7	51.9
2	810.2	851.9	41.7
3	770.2	875.6	105.4
4	710	870.7	160.7
5	735.3	819.2	83.9
6	699.1	841.9	142.8
7	706.1	831	124.9
8	711.8	852.7	140.8

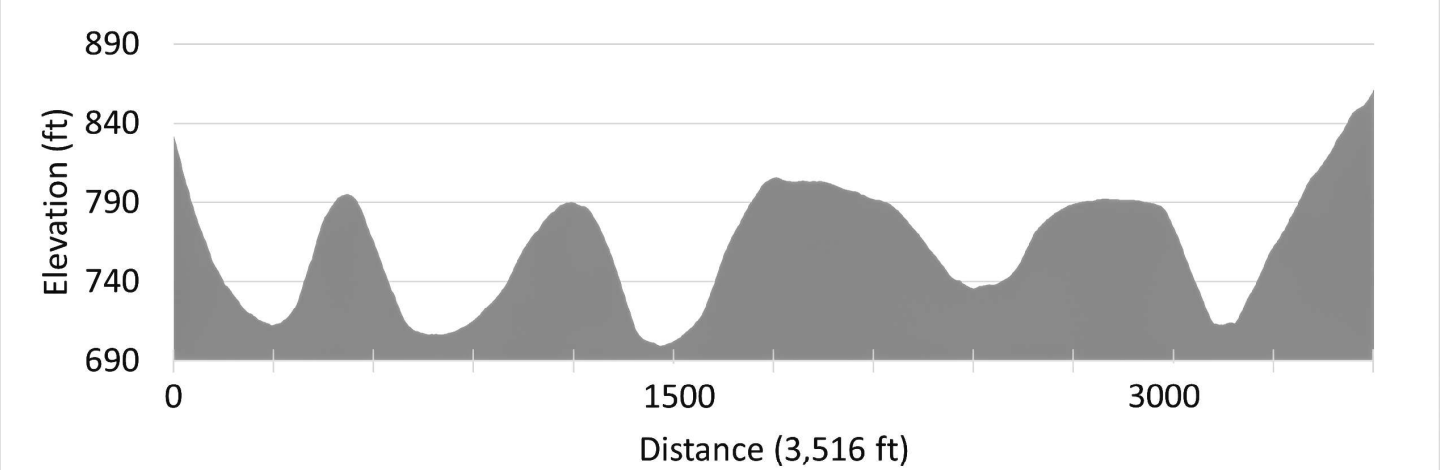


Figure 6. Elevation profiles of Tomahawk Sinkholes 8 through 4 (left to right).

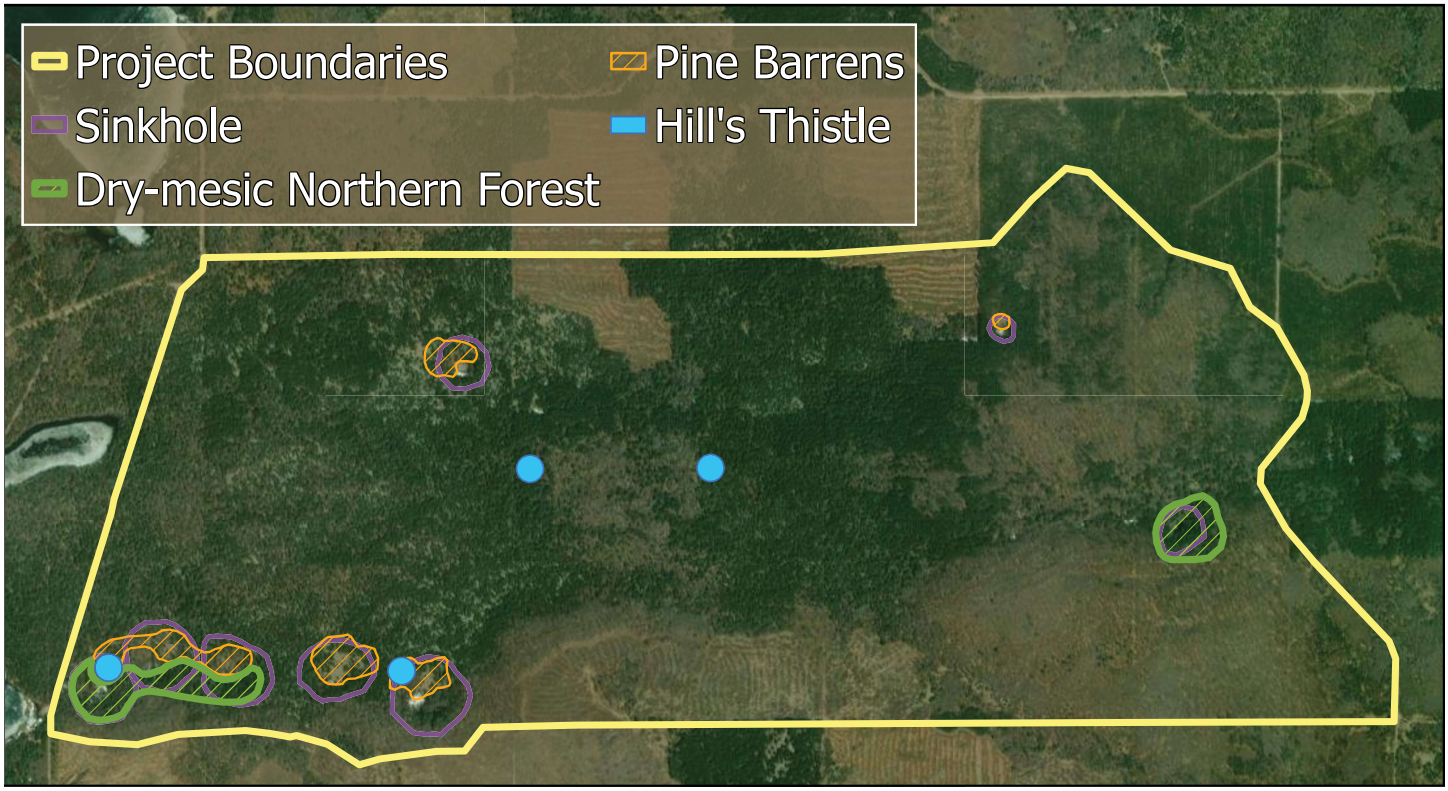


Figure 7. Natural communities and rare plants documented in the Tomahawk Sinkholes and Barrens project area.

(Table 2 and Figure 6). Others are over 160 ft deep and around 400 ft across. Most of the sinkholes are permanently dry but sinkhole 1 appears to be intermittently inundated and there is substantial use by wildlife when there is standing water. Sinkhole 3 has permanent standing water and extensive underwater algal mats or biofilm.

Some areas have extreme erosion from badgers with dozens of dens, both occupied and abandoned, occurring on forested slopes. Soils are generally droughty and acidic sands though composition and pH is variable. A soil sample from the dry-mesic northern forest Sinkhole 3 featured 10 cm of acidic needle duff mixed with decayed organics (pH 5.0), over 6 cm of acidic sand with organics (pH 6.0 to 5.5), over neutral sands with gravel (pH 7.0). Another sample from Sinkhole 4 featured an O-horizon 1.5 cm thick, pH 6.5, under *Carex pensylvanica* duff, over the 7 cm thick A-horizon of fine gray sands (pH 6.0 to 5.5); then the B-horizon of fine tan sands (pH 5.5 to 6.0). There is gravel and glacial erratics at the base of some of the sinkholes.

The sinkholes are in good to fair condition with high-quality natural communities in and around each of the sinkhole features. Generally, these sinkholes support older trees and greater herbaceous diversity than the surrounding landscape. There is localized erosion along trails and viewing areas. Invasive species are also locally abundant but occur at an abundance that could be controlled. Three new sinkholes were identified and described during the surveys of 2023. Two of the new sinkholes had high-quality remnant pine barrens and the third had a high-quality example of dry-mesic northern forest. The existing barrens polygons were refined and a dry-mesic northern forest EO was added to the complex following the 2023 surveys. The Overall Rank of B, or good, was assigned to the sinkholes in 2011 and this rank was confirmed following the 2023 surveys.

Badger dens were frequently encountered during surveys, especially in the forested portions of the sinkholes.

Description of the Tomahawk Pine Barrens
The pine barrens were expanded from 7.0 acres to 15.3 acres following the 2023 surveys. The existing polygons were slightly expanded and additional barrens were documented on two of the newly identified sinkholes. Despite the expansion of the barrens, this remains a very small example occurring only on the steep, south-facing slopes of the sinkholes. The condition of the barrens is generally fair to good with some areas degraded by erosion trending towards poor condition. The sites are extremely diverse for their small size, especially relative to the surrounding landscape. There are local concentrations of invasive species but these are generally at low densities. Barrens were likely historically more prevalent on the landscape but following intensive land clearing, intensive logging, and fire suppression, assemblages of characteristic vegetation have been relegated to the steepest topography of the sinkholes. The primary degrading factors of the barrens remnants are fire suppression facilitating woody encroachment; trails causing localized erosion; and intense deer herbivory. The condition could be improved to a higher rank with frequent prescribed fire; careful redirection of trails; repairing areas impacted by erosion; treating invasive species along trails and in portions of the sinkholes; managing a broader surrounding area as barrens; improving the condition of the matrix between the sinkholes; and reducing populations of deer. The barrens were first described in 2011 and given an overall rank of BC/C. Despite the documentation of additional habitat, this is still a very small barrens remnant and the degradation of landscape context is accelerating so a Rank of C was assigned.

Vegetation is highly variable among the sinkholes. But the canopy tends to be sparse (10 to 20%) and dominated by jack pine (*Pinus banksiana*) with infrequent red pine (*Pinus resinosa*) and northern pin oak (*Quercus ellipsoidalis)*. Small openings that were dominated by a sparse canopy of stunted quaking aspen (*Populus tremuloides*) were included in the barrens area as these featured an herbaceous layer of characteristic vegetation. A red pine had a diameter of 22.3 inches and was estimated to be about 60 years old. A jack pine had a diameter of 16.4 inches and had 63 rings.

Sinkhole 5 looking east towards sinkhole 4. The northern portion of the sinkhole has a southerly aspect, this is the most drought-prone area of the feature and this is where barrens vegetation persists.

The subcanopy is typically sparse but locally dense (10 to 30% coverage) with jack pine and northern pin oak. Other infrequent species include red maple (*Acer rubrum*), white pine (*Pinus strobus*), black cherry (*Prunus serotina*), and occasional white oak (*Quercus alba*). The tall shrub layer is patchy to locally dense (10 to 20%) and features choke cherry (*Prunus virginiana*), American wild plum (*Prunus americana*), beaked hazelnut (*Corylus cornuta*), and hawthorns (*Crataegus schuettei*, and *C. succulenta*). The low shrub layer is patchy to locally dense (10 to 50%) and is especially variable with low sweet blueberry (*Vaccinium angustifolium*), sweetfern (*Comptonia peregrina*), bearberry (*Arctostaphylos uva-ursi*), sand cherry (*Prunus pumila*), round-leaved serviceberry (*Amelanchier sanguinea*), wintergreen (*Gaultheria procumbens*), New Jersey tea (*Ceanothus herbaceus*), fragrant sumac (*Rhus aromatica*), prairie willow (*Salix humilis*), and wild rose (*Rosa blanda*). Huckleberry (*Gaylussacia baccata*) is locally abundant, especially at the upper edges of the sinkholes.

The herb layer is dense (~95% cover of the openings) except where there is localized erosion. Away from areas impacted by erosion, this layer is very diverse. Graminoids are dominant and the most prevalent species include *Carex pensylvanica*, poverty grass (*Danthonia spicata*), little bluestem (*Schizachyrium scoparium*), and big bluestem (*Andropogon gerardii*). Less abundant graminoid species include rice-grass (*Piptatherum pungens*), rough-leaved rice-grass (*Oryzopsis asperifolia*), bluegrass (*Poa saltuensis*), hair grass (*Avenella flexuosa*), panic grasses (*Dichanthelium columbianum*, *D. linearifolium*, and *D. xanthophysum*), slender wheat grass (*Elymus trachycaulus*), prairie brome (*Bromus kalmii*), and false melic (*Schizachne purpurascens*).

Forbs are typically less abundant than graminoids but are diverse in the highest quality areas. Wild strawberry (*Fragaria virginiana*), spreading dog bane (*Apocynum androsaemifolium*), native hawkweeds (*Hieracium gronovii*, *H. kalmii*, *H. venosum*, and *H. scabrum*), goldenrods (*Solidago nemoralis*, *S. hispida*, and *S. speciosa*), field cinquefoil (*Potentilla*

The barrens opening at the top of Sinkhole 4. Thickets of shrubs that historically served as indigenous crops persist on the far slope along the western edge of this sinkhole.

simplex), smooth aster (*Symphyotrichum laeve*), low bindweed (*Calystegia spithamaea*), milkweeds (*Asclepias syriaca* and *A. tuberosa*), harebell (*Campanula rotundifolia*), cow-wheat (*Melampyrum lineare*), pussytoes (*Antennaria howellii*), racemed milkwort (*Polygala polygama*), wormwood (*Artemisia campestris*), wild-bergamot (*Monarda fistulosa*), Canada mayflower (*Maianthemum canadense*), northern blazing star (*Liatris scariosa*), and wood lily (*Lilium philadelphicum*). The Special Concern Hill's thistle (*Cirsium hillii*) is uncommon to locally abundant throughout. Bracken fern (*Pteridium aquilinum*) occurs throughout the area and is most abundant in the margins of the barrens. *Cladonia* lichen occurs in the driest areas and zones near the top that seem to have been impacted by erosion and historic disturbances.

Non-native species are essentially ubiquitous though typically at low densities relative to native vegetation. Morrow's honeysuckle (*Lonicera morrowii*) is the most prevalent invasive shrub. Non-native grasses are infrequent to locally dominant and the most common species include bluegrass species (*Poa pratensis and P. compressa*), quack grass (*Elymus repens*), and tall fescue *(Schedonorus arundinaceus*). Kentucky bluegrass is especially abundant, though it can be difficult to detect later in the season. Non-native invasive forb species are locally dominant and problematic and include common St. John's-wort (*Hypericum perforatum*), non-native hawkweeds (*Hieracium aurantiacum* and *H. caespitosum*), spotted knapweed (*Centaurea stoebe*), leafy spurge (*Euphorbia virgata*), and garden tansy (*Tanacetum vulgare*). These occur along trails and areas where the sinkholes have been impacted by erosion.

The complete species list is provided in Appendix 3. A total of 122 plant species were observed in the barrens with 104 native species (85.2%). The total floristic quality index (FQI) is 42.0, the Total Mean C is 3.8, and the Native Mean C is 4.5. Conservation metrics are available in Appendix 4. As noted, sites are considered regionally significant to the conservation of biodiversity if their FQI is over 35 (Herman et al. 2001).

Diverse assemblages of native vegetation are concentrated around the sinkholes. Species like butterfly weed (pictured above), wood lily, and native hawkweeds are indicative of patches of remnant barrens.

Description of Tomahawk
Dry-mesic Northern Forest

The highest quality forested portions of the sinkholes feature a high-quality dry-mesic northern forest with maturing supercanopy red pine and white pine. The forest, while small, is in relatively good condition with some red pine around 200 years old. Most trees are maturing second growth and around 100 to 130 years old. The forest features surprising diversity given the condition of the surrounding landscape and the community type. The site is impacted by fire suppression, deer herbivory, and a minor component of invasive species. There is an accumulation of coarse woody debris which is expected for a forest of this age. The condition could be improved by allowing low intensity fire; monitoring for and treating invasive species; applying holistic forest management principles to a broader surrounding area; and lowering deer densities.

The relatively closed canopy (~60 to 80%) is dominated by red pine (*Pinus resinosa*), white pine (*P. strobus*), bigtooth aspen (*Populus grandidentata*), and red oak (*Quercus rubra*). Jack pine (*Pinus banksiana*) and red maple (*Acer rubrum*) are relatively infrequent. Supercanopy red and white pine occur throughout with red pine more prevalent in the easternmost sinkhole. Canopy pine are typically 17 to 25 inch dbh. A 20.4 inch red pine was 126 years old. A 21.0 inch dbh red pine had 95 rings. A 21.4 inch dbh red pine had 202 rings. The subcanopy (~30% coverage) is dominated by red maple and red oak with fir (*Abies balsamea*), white pine, and white oak (*Quercus alba*) generally infrequent. The tall shrub layer is variable and diverse with round-leaved dogwood (*Cornus rugosa*), beaked hazelnut (*Corylus cornuta*), juneberry (*Amelanchier arborea*), hawthorns

Sinkhole 3 features a small pool of standing water and supports a forest dominated by mature red pine and white pine. The oldest red pine in this dry-mesic northern forest had 205 rings and occurred along Sinkhole 3.

(*Crataegus schuettei* and *C. succulenta*), and maple-leaved viburnum (*Viburnum acerifolium*) throughout. Low shrubs include snowberry (*Symphoricarpos albus*), blueberries (*Vaccinium angustifolium* and *V. myrtilloides*), bush-honeysuckle (*Diervilla lonicera*), Canada plum (*Prunus nigra*), poison-ivy (*Toxicodendron rydbergii*), and northern dewberry (*Rubus flagellaris*).

The herbaceous layer is diverse in places and nearly absent in others. Prevalent species include wild sarsaparilla (*Aralia nudicaulis*), bracken fern (*Pteridium aquilinum*), rough-leaved rice-grass (*Oryzopsis asperifolia*), Canada mayflower (*Maianthemum canadensis*), spinulose woodfern (*Dryopteris carthusiana*), downy Solomon seal (*Polygonatum pubescens*), and round-lobed hepatica (*Hepatica americana*). The composition becomes more mesic towards the bottom of the sinkholes with bluebead-lily (*Clintonia borealis*), *Carex deweyana*, northern shorthusk (*Brachyelytrum aristosum*), and maidenhair fern (*Adiantum pedatum*). Non-native wall lettuce (*Mycelis muralis*) is locally abundant in areas disturbed by badgers. A total of 65 plant species were observed in the dry-mesic northern forest with 61 native species (93.8%). The total FQI is 31.4, the total Mean C is 3.6, and the Native Mean C is 4.2.

In some areas at the top of the sinkhole, the composition shifts to dry northern forest with sparse red pine canopy, jack pine understory, and a dense huckleberry and blueberry shrub layer. These areas were included in the EO because of the overlap in age and size of the red pine and the relatively good condition of the patches compared to the majority of the surrounding landscape.

Sinkhole 8 looking west towards Shoepac Lake. The supercanopy white pine and red pine of the high-quality dry-mesic northern forest are prevalent along the south and western portions of the sinkhole. Stairs through the barrens on the northern slope are visible in the right of the picture.

Discussion

The Tomahawk Sinkhole site is the only place in Michigan where high-quality pine barrens has been documented within sinkholes. Sinkholes are a critically imperiled community type in Michigan and pine barrens are designated as imperiled. While dry-mesic northern forests are designated as vulnerable, they are still valuable conservation priorities. The Tomahawk Sinkholes are a unique geologic feature that has allowed small but diverse examples of pine barrens and dry-mesic northern forest to persist on a landscape that is being degraded by intensive forestry operations. This collection of natural communities is extremely unusual and the surrounding landscape is worthy of a more holistic approach to management that includes the application of prescribed fire; tempered forestry practices; and infrastructure for recreational access.

This ecological evaluation resulted in the documentation of three additional sinkholes, an expansion of the pine barrens from 7.0 acres to 15.3 acres, and the addition of a 15.1 acre dry-mesic northern forest. We also documented new locations of the rare Hill's thistle (State Special Concern). Despite the occurrence of high-quality natural communities at the site, there are serious threats jeopardizing the long-term potential for the remnants to persist. This important conservation site needs continuing stewardship and for that stewardship to be applied to a broader area.

Element Occurrence Rank

The overall rank of a natural community EO is a combination of the Landscape Rank, Size Rank, and Condition Rank. Within this discussion section, we describe the components of the Element Occurrence rank of Tomahawk Sinkholes, Pine Barrens, and Dry-mesic Northern Forest. The compiled ranks provide a comprehensive description of the sinkholes and surrounding landscape and inform specific stewardship recommendations provided in the following Management Considerations section.

Landscape Rank

Historically, pine barrens occurred as a shifting mosaic where the community type occurred in a matrix of dry pine forest and savanna and expressions of the systems moved through complex interplay between Indigenous occupancy, herbivores, fire, soil conditions, and climate. Notes from GLO surveyor George H. Cannon describe the landscape as "mostly burnt" in 1851. Expressions of barrens likely developed where Indigenous cultural fires were most frequent and where features on the landscape promoted open conditions: depressions acting as frost pockets; drainages with deep sands; and drought-prone south-facing slopes. Catastrophic, stand-replacing fires would have infrequently impacted areas during prolonged drought.

Several forested stands in the matrix between sinkholes support characteristic barrens vegetation such as big bluestem, wood lily, and Hill's thistle. Stand 38 in 2022 prior to being clearcut, trenched, and sprayed with herbicide.

Humans potentially influenced patterns of herbivore grazing through careful application of frequent, low-intensity fire, creating this dynamic landscape of roving, fire-adapted communities: the shifting mosaic. Within such a landscape of frequent fire, mobile populations of large herbivores, and unbroken natural cover, barrens were likely a much more prevalent and consistent feature of the broad dry northern forest matrix. However, the late stages of Euro-colonization halted the processes that governed the barrens continuum and the mosaic ceased shifting. The barrens vegetation became fixed and then reduced by fire suppression, which increased canopy closure across the landscape. The barrens vegetation persisted only in the landscape positions with abiotic forces that prevented conversion to forest: the sinkholes. Remaining concentrations of barrens species occur in the sinkholes where intensive land management has not eliminated the characteristic vegetation.

Today the region features extensive State Forest land characterized by natural cover consisting of early to mid-successional forests. The landscape between the sinkholes is primarily second-growth red and jack pine forest (dry northern forest) with white pine, red oak, northern pin oak, and infrequent white oak as forest canopy associates. Occasional red pine stumps from the major logging events of the 19th century remain on the landscape. Some older trees also remain on the landscape but the vast majority are under 100 years-old. A 71.4 cm dbh red pine in Stand 94 had 141 rings. The oldest tree documented on the landscape was a 66 cm dbh red pine north of Sinkhole 6. It was partially rotten in the center and 19.2 cm of the core from this tree had 175 rings and the tree was estimated to be between 290 and 320 years old assuming a constant rate of growth. This likely reflects the age of many of the trees prior to logging in the late 1800s.

The Tomahawk Sinkholes, Pine Barrens, and Dry-mesic Northern Forest occur within a landscape that is being managed for timber and early-successional forest. Forestry management techniques such as clearcuts and conversion of natural forest to plantation using trenching and herbicide appear to be accelerating. This is degrading the landscape and is eliminating areas of recoverable barrens in the forested matrix between the sinkholes. Stand 38 had several diverse areas with characteristic barrens vegetation before it was clearcut, trenched, and herbicided in 2023. Degraded forests that have not been converted to pine plantation generally have extremely low diversity, and sparse vegetation with extensive *Cladonia* lichen. Less intensively managed forests feature natural red pine and extensive huckleberry and low sweet blueberry. High deer densities are limiting regeneration of many components of the heavily managed forests. Many plant species disappear following forestry treatments and once-diverse assemblages of vegetation are being replaced with a limited subset of species (Bassett and Lincoln 2024).

Current, intensive forestry practices are permanently eliminating areas of recoverable pine barrens. Stand 38 in 2023.

For each of the three EOs we assigned a landscape context rank of C. The landscape rank of C is justified because of the extent of natural cover on the surrounding landscape, despite degrading factors. The primary degrading factors are the high levels of deer; the very narrow application of fire on a landscape featuring extensive fire-dependent communities; the high degree of herbicide application and furrowing; the prevalence of plantations and young, degraded forests; the paucity of older forests with any potential to approach old growth conditions; and the high degree of fragmentation from logging or ATV roads. These are all contributing to a region-wide decline in diversity. Without landscape-scale stewardship intervention, the plantations and third-growth forests that characterize the landscape are unrecoverable to conditions resembling natural communities. The landscape rank will likely continue to be reduced due to these degrading factors.

Size Rank

The 8 sinkholes were expanded from 24.0 to 38.0 acres and have a size rank of B, or moderate size. The pine barrens were increased from 7.0 to 15.3 acres following the 2023 surveys and are still very small, or “D-rank”. The dry-mesic northern forest is 15.1 acres and also very small. With stewardship intervention, parts of the surrounding landscape may be recoverable to barrens worthy of inclusion in the EO. There is excellent potential to increase the size of the pine barrens EO by developing a barrens restoration project area and applying the ongoing restoration efforts to more of the surrounding landscape between the sinkholes in Stands 48, 102, and portions of 98 and 83. Southern Stand 38 especially had concentrations of barrens vegetation prior to being clearcut, trenched, and sprayed with herbicide. Stand 38 should be continually evaluated for concentrations of surviving barrens species. Stand 1 in Compartment 54123 also had barrens indicator species and additional recoverable habitat may persist along a small drainage to the northwest in Stand 135 of Compartment 54120 (Table 3). There are also likely additional sinkholes in the surrounding region, though these appear to be primarily on private land (Figure 8). Additional surveys are warranted because of the elevated plant diversity associated with sinkholes and the potential for them to increase in importance for climate refugia. If encountered, additional sinkholes should be judiciously managed with large buffers established around them to prevent degradation from intensive forestry practices such as clear-cutting and application of herbicide. There is a very low probability of identifying additional areas of high-quality forest worthy of inclusion in the dry-mesic northern forest EO.

There is still extensive natural cover around several of the sinkholes. The barrens openings are evident and could be expanded through consistent application of periodic fire and judicious timber harvest to promote a more diverse and resilient landscape.

Table 3. Potential areas of barrens vegetation. Concentrations of barrens vegetation persist on the landscape and could be the focus of future restoration efforts. Areas to evaluate for inclusion in restoration projects are provided below.

Compartment	Stand	Description
	38	Southern portion had openings with barrens vegetation prior to clearcut
54120	65	Pockets of barrens vegetation
	90	Small patches of barrens vegetation prior to clearcut
	102	Concentrations of barrens species, Morrow's honeysuckle invading
	1	composition along road, too small for EO
54123	4	small openings in western portion
	5	small openings in western portion

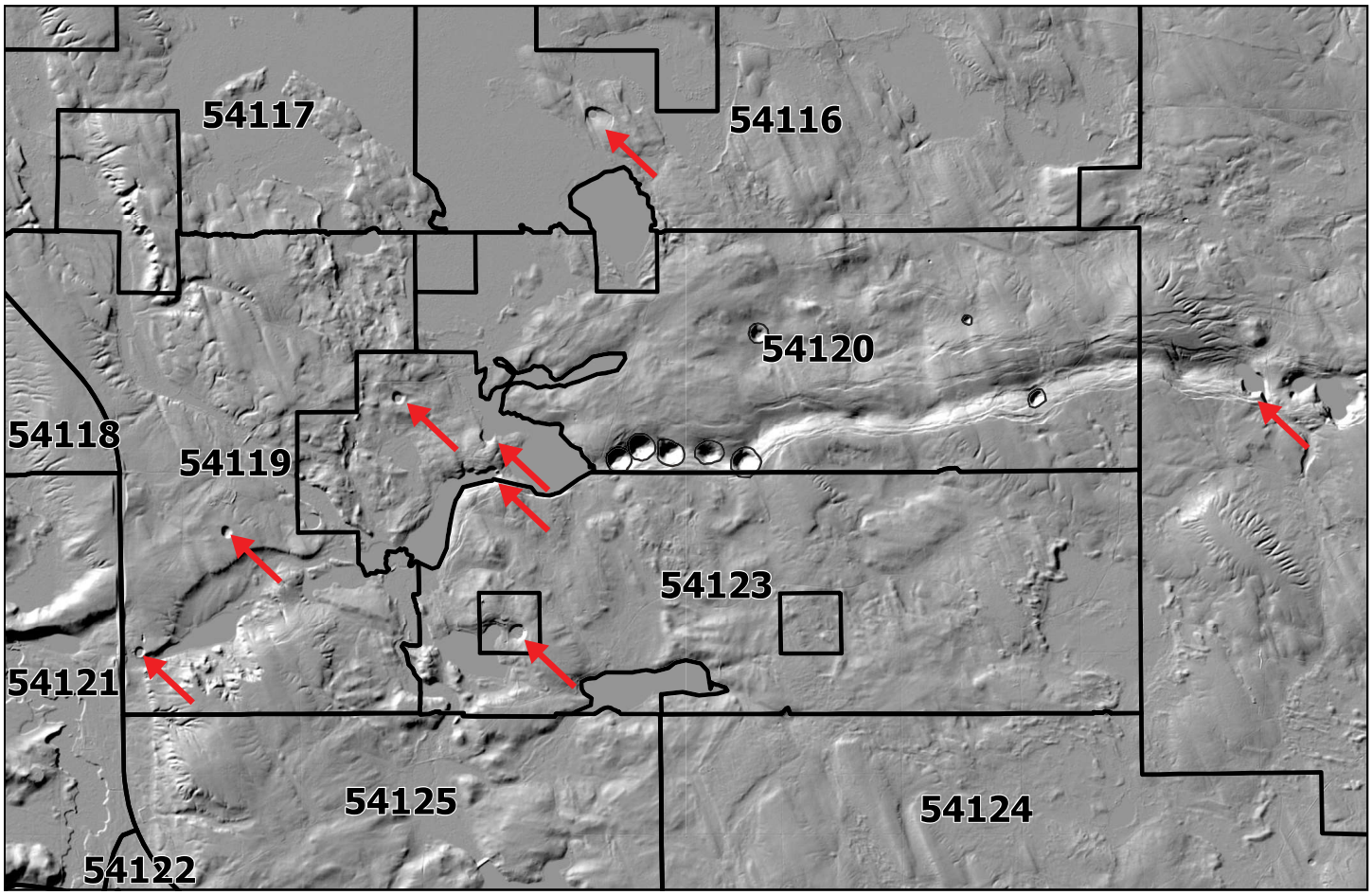


Figure 8. A digital elevation model of the area reveals several additional sinkholes on the surrounding landscape (red arrows). Many of these are on private property but those on public land should be surveyed for conservation opportunities.

Condition Rank

Generally the sinkholes, pine barrens, and dry-mesic northern forest are in good to fair condition and are extremely diverse, especially relative to the surrounding landscape. The sinkholes often have a concentration of plants that were likely culturally significant resources to Indigenous Peoples. These include choke cherry (*Prunus virginiana*), beaked hazelnut (*Corylus cornuta*), huckleberry (*Gaylussacia baccata*), low sweet blueberry (*Vaccinium angustifolium*), American plum (*Prunus americana*), sweetfern (*Comptonia peregrina*), bearberry (*Arctostaphylos uva-ursi*), serviceberry (*Amelanchier interior*), sand cherry (*Prunus pumila*), and round-leaved serviceberry (*Amelanchier sanguinea*).

Other areas of open barrens are being encroached upon by woody vegetation such as aspen and jack pine, thereby eliminating characteristic open canopy structure and suppressing herbaceous vegetation. Some areas are trending towards poor condition due to erosion exacerbated by a trail system. Invasive species are ubiquitous but generally at low densities if locally dominant along trails and areas of severe erosion.

Pine barrens historically functioned in a landscape characterized by a shifting mosaic and were likely historically more prevalent on the landscape. Within this historic landscape context, plant populations fluctuated and were replenished by metapopulations. Following intensive logging, current intensive forestry approaches, and fire suppression, these assemblages have been relegated to the steepest topography of the sinkholes. The current static landscape, absence of fire, lack of herbivores, and continual forces of degradation creating an increasingly hostile matrix will cause major components of the community to stochastically disappear with dwindling probability for replacement.

The primary degrading factors are fire suppression facilitating woody encroachment, trails causing localized erosion, locally problematic invasive species, and intense deer herbivory. The condition of the barrens could be improved with frequent prescribed fire; careful redirection of trails; repairing areas impacted by erosion; treating invasive species along trails and in portions of the sinkholes; expanding the area managed as barrens; and by improving the condition of the matrix between the sinkholes.

Aspen is closing in portions of the barrens (Sinkhole 6, pictured) but characteristic herbaceous species persist and the condition of such areas can be improved by restoring barrens structure with frequent fire.

Sinkhole 5 in 2011 (top, photo by J.G. Cohen) and 2023 (bottom). Woody encroachment by jack pine has increased as has the area of exposed sand caused by foot traffic.

Management Considerations

The condition of the Tomahawk Sinkholes, Pine Barrens, and Dry-mesic Northern Forest could be improved with stewardship intervention. We offer a management approach that promotes the resilience of the rare natural communities at the site. This will protect local biodiversity, maximize resiliency to climate change, and mitigate ecological and economic costs associated with intensive forestry management techniques such as trenching and applying herbicide.

We recommend that managers establish a large project area to improve conditions to secure the sinkholes and barrens habitat. Within the project area we encourage resource managers to manage the barrens remnants and the surrounding landscape with prescribed fire; limit loss of biodiversity by establishing a matrix of connectivity, primarily by managing the project area as dry northern forest with pine barrens and inclusions; provide habitat that meets multiple objectives, including promoting habitat for Kirtland's warbler and other rare species identified in the state's Wildlife Action Plan (Derosier et al. 2015). We believe this management approach can be conducted in a way that also benefits games species (e.g., deer, elk, and grouse) and allows for timber harvest focused in the least ecologically sensitive areas. Not all areas within the proposed project area are high diversity but this approach will buffer existing areas of high-quality natural communities.

To achieve this, we propose 1) establishing a large project area around the sinkholes; 2) developing smaller Priority Conservation Areas (PCAs) around sinkholes to facilitate the implementation of prescribed fire; and 3) developing Intermediate Management Zones (IMZs) within the project area that will be managed with periodic fire and less intensive timber harvests to maintain natural forest and express remnant pockets of barrens vegetation that may persist (Figure 9).

Implementation

Phase 1: Create a large project area around all of the sinkholes and forested matrix between sinkholes.

- Temporarily halt timber harvests within project area
- Halt application of herbicide within project area
- Maximize inclusion of recoverable, non-plantation forest

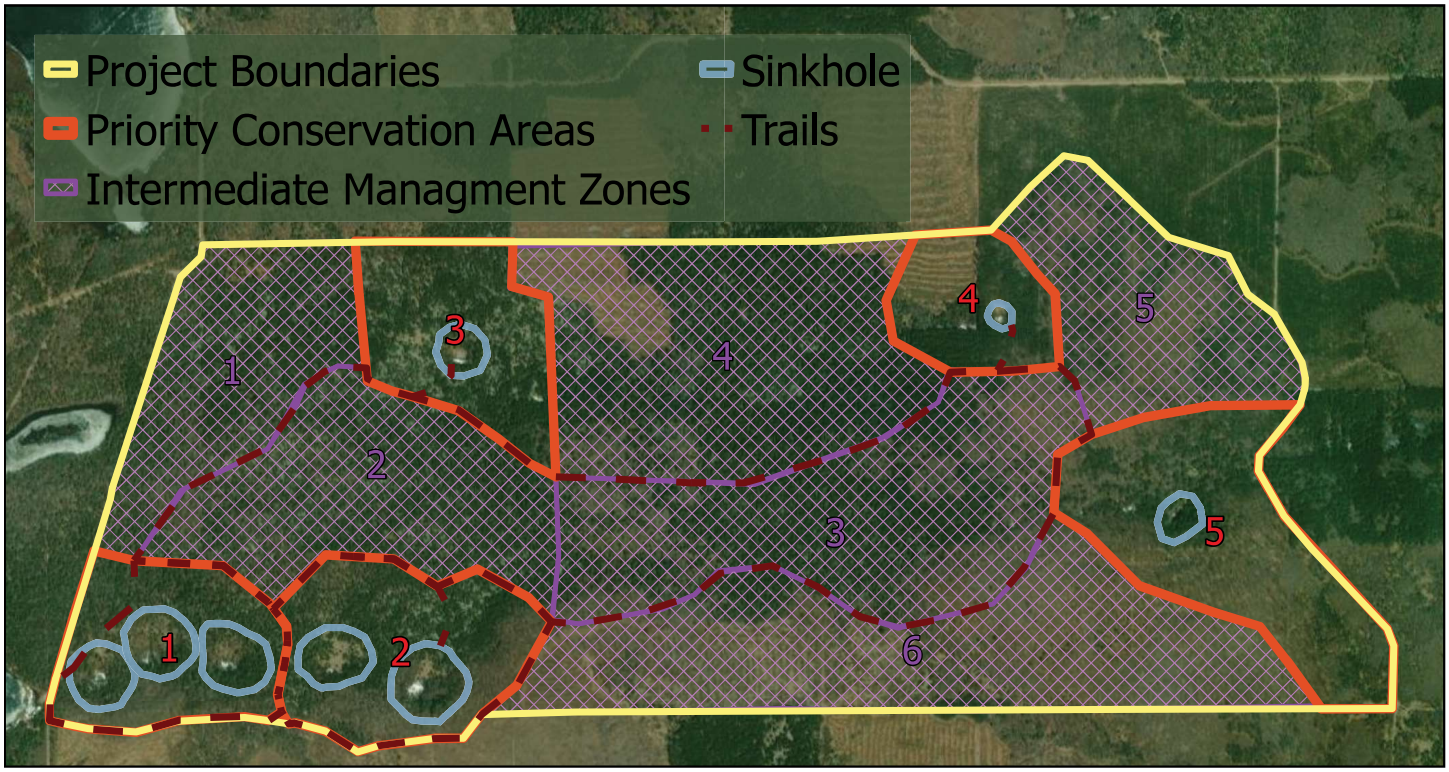


Figure 9. The proposed Project Area for Tomahawk Sinkholes. The Tomahawk Sinkhole site is a unique conservation opportunity and our recommended management approach is designed around developing a large project area, establishing Priority Conservation Areas (PCAs) within that project area, and developing Intermediate Management Zones (IMZs) between the PCAs. Existing trails should be relocated and serve as the boundaries of PCAs as well as burn breaks. Stewardship would initially be focused in the PCAs where fire would be applied at a relatively high frequency to promote barrens habitat. IMZs would ideally feature a management approach that balances ecosystem management principles with infrequent timber harvest to promote an improved ecological integrity within the matrix between sinkholes.

Phase 2: Within the broader project area, establish various management zones and relocate trails to protect sensitive habitats.

Priority Conservation Areas (PCAs): these will function as buffers around sinkholes and focus expansion of barrens habitat around existing remnants of recoverable barrens habitat within the matrix between sinkholes.

- One of the main goals for the PCAs is to expand barrens habitat. Each sinkhole will be unique but we anticipate that barrens vegetation will slowly expand to a greater extent with our outlined management approach. The canopy of this area will ideally be variable with 5 to 60% canopy coverage, primarily red pine, jack pine, northern pin oak, and white oak. Some areas will also likely have thickets of aspen. A key priority is to ensure that barrens composition is not being eliminated by conversion to forest.
- The southern portions of the sinkholes feature dry-mesic to dry northern forest and this is an ideal habitat for this landscape position. Intense fire and tree removal are not a priority in the areas on the southern portions of the sinkhole and barrens expansion should be focused elsewhere.
- Eliminate commercial timber harvests from the PCAs. The only need for mechanical intervention is to promote the expansion of barrens structure and composition. Some mechanical work may be necessary to prepare the site for its initial burn or to control invasive species or native trees such as aspen and jack pine which may readily invade barrens zones.
- Develop a trail network that can function as boundaries of the PCAs as well as burn breaks. To best accomplish this, we urge managers to move existing trails away from the upper margins of the sinkholes to limit the extent of trails in the most sensitive areas; mitigate the most serious erosion issues through erosion mats or planting native species; limit the number of sinkholes visited by the trail system; and to develop minimal infrastructure to withstand fire. One option might be to make small gravel platforms with stone edging to provide viewing areas that are resilient to fire and do not cause erosion on the steep slopes of the sinkholes
- Prioritize invasive species control within the PCAs. Reduce invasive species that are accessible along existing trails. Sinkhole 5: Garden tansy (*Tancetum vulgare*) is prevalent at the base of the slope in Sinkhole 5. Leafy spurge (*Euphorbia virgata*) and tall fescue (*Lolium arundinaceum*) are locally abundant in Sinkhole 4 near the top where there is localized erosion. Morrow honeysuckle (*Lonicera morrowii*) is locally abundant throughout the project area and should be treated when encountered.

Intermediate Management Zones (IMZs): The primary purpose for these areas is to improve the matrix habitat between sinkholes to promote barrens vegetation and natural pine forest while allowing low-impact forestry operations to occur periodically.

- The IMZs should be managed as a natural, sparsely canopied pine-dominated forest with sparse red pine, jack pine, and white pine with occasional northern pin oak, white oak, aspen, and red oak. This is a large project area and composition will be variable across the landscape.
- Retain the oldest red pine, white pine, and red oak as the project area is established. Retain all white oak and avoid damaging important Indigenous shrub crops listed above.
- The IMZs will ideally have small retention pockets that preclude timber harvest where old growth is allowed to develop, older cohorts can persist, and no mechanical disturbance occurs to protect the understory and herbaceous composition.
- Continue the trail network to function as boundaries of IMZs and burn breaks and to connect the sinkholes to the trail network when applicable.
- Within the IMZ we recommend a lower frequency of prescribed fire than recommended in the PCAs (see below). The fire return interval in the IMZs should be every 10 to 20 years followed by a timber harvest roughly every 30 years where the canopy is not reduced below 50% canopy coverage. These areas should be continually monitored for the expression of barrens indicator species to help direct future restoration efforts. We also recommend halting the widespread application of herbicide to promote a more diverse, recoverable landscape in the project area.

Phase 3: Return fire to the landscape.

- Focus fire initially within the PCAs with low-intensity, low-severity, late-season burns. Specifically, focus fire in the highest quality PCAs first; apply fire at a relatively high frequency of about 2 burns per decade. Avoid equipment in the barrens remnants and at the tops of sinkholes to prevent erosion and harm to the highest quality areas. Include the high-quality forests on the southern portions of the sinkholes but don't target these areas and avoid crown fires or mortality in canopy trees by conducting late-season burns .
- Include IMZs in prescribed fires once fire has successfully been returned to the highest quality PCAs. Maintain forested structure and minimize mechanical work ahead of fires. The initial burns should be low intensity, low severity to avoid crown fires which may be best achieved with late season burns (late September through November). Apply burns every 10 to 20 years with timber harvest (moderate thinning) occurring after the burns.

In general, we do not recommend managers supplement the species composition by planting additional species. Doing so jeopardizes the site's status as a valuable reference area, and herbaceous diversity is already locally high. However, much of the site has been impacted by timber harvests, trenching, planting pine, and widespread application of herbicide. Consequently, much of the proposed project area lacks the characteristic barrens structure in several areas. To improve conditions, especially in areas impacted by erosion along the sinkholes, planting of native herbaceous species may be necessary and we suggest managers select species observed at the site from the list provided in the appendix. Likewise, it may be necessary to improve composition of areas degraded by ongoing management practices by adding native trees, shrubs, and herbaceous species.

Following the management approach outlined here, the project area will feature a variable canopy. Overall canopy coverage across the entire project area maybe around 50% or more, but barrens areas will ideally feature a canopy of around 5 to 60% canopy coverage and some forested areas will have a nearly closed canopy. Overall, red pine and jack pine will be the most dominant trees, have a similar prevalence, and comprise about 70% of the canopy. White pine will be a lower abundance with infrequent aspen and oak and very little cherry. Some of the red pine should be allowed to reach ages of 200 to 300 years and the widely spaced nature should prevent catastrophic crown fires that engulf the entire area, even if many jack pine are consumed. These are general guidelines and can be adjusted over time as the response to the shift in management approach is evaluated.

This approach is intended to maximize overlap of biodiversity management; climate change and wildfire resilience; and periodic timber harvest. The resulting landscape will feature a canopy with widely distributed age classes, tree densities, and complex composition corresponding to landscape position. It is difficult to predict the extent to which barrens habitat will expand under this management approach, but we encourage maximizing barrens extent as characteristic savanna structure and composition is developed under this holistic approach.

Applying Prescribed Burns

Prescribed burns are instrumental in the maintenance of pine barrens and dry-mesic northern forests. We urge managers to apply prescribed fire across a large area that includes more forested stands in the matrix between sinkholes. Fire has several benefits that cannot be replicated by other management techniques. Fire can typically adequately regenerate red pine in natural pine forests and avoids ecological costs caused by herbicide and clear-cutting. Fire is the primary historic disturbance factor that influenced the dry pine forests of the region and remains an important part of the culture of the Indigenous Peoples of the region. Many plant species are fire adapted and fruiting of several species of cultural and wildlife value are enhanced by fire.

Recent evidence from tree and stump cores in the Upper Great Lakes suggests a higher frequency of historical surface fires in red pine–dominated systems than was previously understood. Low-intensity surface fires occurred every 5 to 20 years in fire-dependent ecosystems across Upper Michigan. Frequency is particularly important for red pine regeneration where frequencies must be high enough to create suitable conditions for establishment that coincide with large red pine seed crops that only occur every five to ten years (Kozlowski and Ahlgren 1974; Horton and Bedell 1960). High fire frequencies deplet mesophytic species over long-time scales and keep fuel levels low, reducing the risk of more severe fires (Nowacki and Abrams 2008). We recommend using the estimated historical frequency of a fire every 5 to 20 years as a baseline for long-term maintenance of dry northern forest and dry-mesic northern forest. More frequent burns, two to three per decade, may be necessary initially, depending on the history of the stand and available fuel, to provide a competitive advantage to fire-adapted plants and regenerate red pine. There are several large red pine stumps on the landscape and these should be evaluated for fire scars to determine the historic fire regime.

Evidence from the Upper Peninsula shows that fires occurred disproportionately during the dormant season (late fall to early spring) based on fire scar positions relative to growth rings (Sutheimer et al. 2021; Muzika et al. 2015). Dormant season burns may increase the number of pine seeds reaching mineral soil depending on the timing of seed rain, which usually peaks in early fall. Spring and early summer burns create more competition from early plant colonizers that can become established before the peak of red pine seed rain (Kozlowski and Ahlgren 1974). Applying fires in late autumn (late September to November) may also lower the risk of severe crown fires in jack pine and red pine forests (Jolly 2016). The reintroduction of fire to areas where it has been absent for nearly a century poses several challenges. In addition to socio-cultural concerns, high fuel loads need to be considered. Large red pine boles are strongly resistant to mortality from low-intensity surface fires, even with high fuel loads (Scherer et al. 2016); however, raking away fine fuels from ecologically valuable old trees may be necessary to reduce the risk of mortality and injury. High density of understory trees increase the risk of crown fires and it may be necessary to mechanically remove some understory trees before introducing fire to stands with dense understories.

Fire will ideally be applied differently in the PCAs and IMZs. Within the PCAs, fire can be applied at a relatively high frequency of 1 to 2 burns per decade. Fire can be applied at a lower frequency within the IMZs at a rate of a burn every 10 to 20 years. Because of the extreme flammability of pine dominated systems, fires in both PCAs and IMZs should be of relatively low intensity so as not to kill canopy trees or create crown fires. To accomplish this, we suggest that burns are conducted in late fall or early winter to mimic historical timing of burns. This approach of employing low intensity fires is especially important when introducing fire to areas that have not been recently burned. A goal of the initial fires is to consume ladder fuel and fuel on the ground without killing more than 10% of the canopy trees or causing a crown fire. Such burns may not appear to be having a dramatic impact but over time they fundamentally alter and improve the structure and composition of the barrens and natural pine forests without destroying canopy trees.

Benefits to Wildlife

Fire in barrens and dry-mesic northern forests provides several benefits to game species. We have observed flushes of aspen following fire and detected positive responses from grouse. Browse from white-tailed deer is also observed to be more prevalent in natural forests that had been burned compared to adjacent forests that were not burned.

Beyond the benefits to game species, a return of widespread fire on the landscape as a tool for ecosystem management would benefit several rare species. Kirtland's warbler (*Setophaga kirtlandii*; State Endangered) is one of the rarest, most geographically restricted birds of North America. A portion of its breeding area occurs just south of Tomahawk Barrens. Historically, this species was dependent on jack pine forests that regenerated after fire. The warblers occupy stands with 5- to 23-year-old jack pine (Probst 1988). This range of jack pine ages almost perfectly matches the documented return interval of cultural fire within the natural pine stands of the central Upper Peninsula (Anderton 1999) and is an appropriate frequency to apply fire in the Tomahawk Barrens project area. Forests that have been burned are occupied by Kirtland's Warblers at higher rates and for greater durations than unburned forests (Probst and Hayes 1987). This once Federally Endangered species has been delisted in large part due to establishment of plantations. It seems its decline, like the decline of natural red pine, can be closely attributed to the cessation of Indigenous cultural fires. Our management recommendations for the PCAs and IMZs are in line with the creation and maintenance of Kirtland's warbler breeding habitat.

Additional rare species would also benefit from our recommended management approach. Rare species that may benefit from prescribed fire include eastern whip-poor-will (*Antrostomus vociferus*; State Threatened), upland sandpiper (*Bartramia longicauda*; State Threatened), spruce grouse (*Canachites canadensis*; State Threatened), common nighthawk (*Chordeiles minor*; State Special Concern), evening grosbeak (*Coccothraustes vespertinus*; State Threatened), northern flying squirrel (*Glaucomys sabrinus*; State Special Concern), Connecticut warbler (*Oporornis agilis*; State Special Concern), smooth green snake (*Opheodrys vernalis*; State Special Concern), Black-backed woodpecker (*Picoides arcticus*; State Special Concern), northern blue (*Plebejus idas nabokovi*; State Threatened), and sharp-tailed grouse (*Tympanuchus phasianellus*; State Special Concern).

Future Work

This site would benefit from future work. In particular, long-term vegetation monitoring should be established in the sinkholes and pine barrens to evaluate changes to vegetation over time and in response to stewardship actions. Because the proposed management recommendations have the potential to beneficially impact rare animals such as Kirtland's warbler, periodic animal surveys are also warranted. The proposed management approach of combining low intensity, low severity fires with periodic thinning of the canopy is a unique approach and should be evaluated to determine efficiency of natural regeneration, impacts to vegetation composition, and demographics of canopy associates over time. Continual monitoring and treatment of invasive species is also important ongoing work.

The widespread availability of LiDAR has improved our ability to detect sinkhole features and given the rarity of sinkholes in Michigan and the local concentration of karst features, efforts to identify additional sinkholes on state land should be undertaken and sinkholes on nearby private land should be prioritized for protection. Finally, many of the species observed at the site had not been collected from the county. There are several species near their northern extent and many others that have not been documented from the area. In particular, collections of hawthorn from the site are required for conclusive identification and the species identified in this report are only cursory. We recommend an update to this ecological evaluation in 2034 with a focus on vegetation monitoring and collection of plants for updating herbaria records.

Concluding Remarks

This ecological evaluation resulted in the identification of three additional sinkholes, expanded the existing pine barrens EO, identified a previously undocumented high-quality dry-mesic northern forest, and located a new population of special concern Hill's thistle at the Tomahawk Sinkhole site. With only five sinkholes documented in Michigan, they are a critically imperiled community type in the state. The Tomahawk Sinkholes are a unique geologic feature that has allowed small but diverse examples of pine barrens and dry-mesic northern forest to persist on a landscape that is being degraded by intensive forestry operations. This mosaic of natural communities is unusual and the landscape is worthy of a holistic management approach that includes the application of prescribed fire and less intensive forestry practices.

Pine barrens were part of a shifting landscape where plant populations fluctuated and were replenished by metapopulations. Following intensive logging, and fire suppression, these assemblages have been relegated to the steepest topography of the sinkholes. The sinkholes have concentrations of conservative plant species and much greater species richness compared to surrounding forests. These clusters of barrens vegetation in the sinkholes are patches of a once-widespread system lingering in landscape positions that avoided degradation and resist forestation. While vegetation can persist in diminished, non-flowering forms for decades and in the seedbank for longer, the chance for recovery of barrens remnants decreases over time. Current forestry practices and the absence of fire is causing an increasingly hostile matrix between sinkholes where barrens species stochastically disappear with dwindling probability for replacement.

Many natural forests are being converted to pine plantation across State Forest lands. Plantations were initially developed as a tool to stabilize a landscape catastrophically altered by European colonization. The ongoing conversion of natural forests to plantations, often with the broadcast application of herbicide, is degrading state-owned natural areas at an increasing rate. Common practices of scarification, furrowing, and herbiciding irreparably degrades the landscape through elimination of principle components of the ecosystems. Stand 38 in Compartment 54120 was clearcut, trenched, herbicided, and converted from a natural forest to a plantation, despite containing several areas of high-quality barrens vegetation. This management approach negatively impacts the ground layer by reducing low-shrubs, flowering plants, and grasses. The ground layer typically accounts for most plant diversity in dry northern forests and is thus of critical importance when managing stands for ecological, cultural, and wildlife value. Additionally, plantations are especially vulnerable to the increasing volatility of climate change.

An area within the proposed project area that had been a stand of natural pine and featured concentrations of barrens species. It has since been clearcut and trenched in preparation for conversion to a plantation, thereby eliminating elements of recoverable pine barrens. Current management approaches to the landscape preclude the retention of natural communities.

In this report, we have outlined an alternative management approach to protect the sinkholes and expand this important example of pine barrens. We recommend that managers establish a large project area to improve conditions to secure the sinkholes and barrens habitat. Within the project area we encourage resource managers to manage the barrens remnants and the surrounding landscape with prescribed fire; limit loss of biodiversity by establishing a matrix of connectivity, primarily by managing the project area as dry northern forest with pine barrens inclusions; provide habitat that meets multiple objectives, including promoting habitat for Kirtland's warbler and other rare species identified in the state's Wildlife Action Plan. We believe this management approach benefits games species such as deer, elk, and grouse and allows for periodic timber harvest in the least ecologically sensitive areas. With continued management and monitoring, our approach will protect and expand existing barrens and identify additional recoverable natural communities and prevent local extinctions for a more resilient and diverse landscape.

If enacted, the approach outlined in this report will improve the condition of natural communities; improve habitat for game species; create a landscape more resilient to climate change; and ultimately contribute to the local economy in a stable way through forestry treatments that maintain natural conditions We hope that this ecological evaluation of Tomahawk Sinkholes will support and guide the future endeavors to protect and preserve this valuable piece of our natural heritage.

The Tomahawk Pine Barrens supports several areas with barrens structure and composition. With the application of fire and expansion of the area managed as pine barrens, the site and landscape will improve and remain an important reservoir for native biodiversity.

Literature Cited

Albert, D.A. 1995. Regional landscape ecosystems of Michigan, Minnesota, and Wisconsin: A working map and classification. USDA, Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Anderton, J.B. 1999. Native American Fire-Maintained Blueberry Patches in the Coastal Pine Forests of the Northern Great Lakes. The Great Lakes Geographer 6:1-2: 29-39

Bassett, T.J. and J.M. Lincoln. 2024. Baseline sampling of jack pine ecosystems in the Kirtland's Warbler Wildlife Management Area. Michigan Natural Features Inventory, Report No. 2024-01, Lansing, MI.

Black, T.J. and C. Gregory. 1995. Karst Geology of the Northeast Lower Peninsula, Michigan. Michigan Basin Geological Society American Institute of Professional Geologists and Michigan Karst Conservancy.

Chapman, K.A. and R. Brewer. 2008. Prairie and Savanna in Southern Lower Michigan: History, Classification, Ecology. The Michigan Botanist; Vol 47, pp 1-48.

Cohen, J.G., M.A. Kost, B.S. Slaughter, and D.A. Albert. 2015. A Field Guide to the Natural Communities of Michigan. Michigan State University Press, East Lansing, MI. 362 pp.

Cohen, J.G., C.M. Wilton, H.D. Enander, and T.J. Bassett. 2021. Assessing the Ecological Need for Prescribed Fire in Michigan Using GIS-Based Multicriteria Decision Analysis: Igniting Fire Gaps. Diversity 13(3).

Cohen, J.G.; Kost, M.A.; Slaughter, B.S.; Albert, D.A.; Lincoln, J.M.; Kortenhoven, A.P.; Wilton, C.M.; Enander, H.D.; Korroch, K.M. Accessed December 2022. Michigan Natural Community Classification; Michigan Natural Features Inventory, Michigan State University Extension: Lansing, MI, USA, 2020; Available online: https://mnfi.anr.msu.edu/communities/classification.

Comer, P.J., D.A. Albert, H.A. Wells, B.L. Hart, J.B. Raab, D.L. Price, D.M. Kashian, R.A. Corner, and D.W. Schuen. 1995. Michigan's presettlement vegetation, as interpreted from the General Land Office Surveys 1816-1856. Michigan Natural Features Inventory, Lansing, MI. Digital map.

Comer P.J. 1996. Natural community abstract for pine barrens. Michigan Natural Features Inventory, Lansing, MI. 4 pp.

Derosier, A.L., S.K. Hanshue, K.E. Wehrly, J.K. Farkas, and M.J. Nichols. 2015. Michigan's Wildlife Action Plan. Michigan Department of Natural Resources, Lansing, MI. www.michigan.gov/dnrwildlifeactionpla

Faber-Langendoen, D., J. Rocchio, P. Comer, G. Kudray, L. Vance, E. Byers, M. Schafale, C. Nordman, E. Muldavin, G. Kittel, L. Sneddon, M. Pyne, and S. Menard. 2008. Overview of Natural Heritage Methodology for Ecological Element Occurrence Ranking based on Ecological Integrity Assessment Methods [Draft for Network Review]. NatureServe, Arlington, VA.

Faber-Langendoen, D., W. Nichols, J. Rocchio, J. Cohen, J. Lemly, and K. Walz. 2015. Ecological Integrity Assessments and the Conservation Value of Ecosystem Occurrences: General Guidance on Core Heritage Methodology for Element Occurrence Ranking. NatureServe, Arlington, VA.

Freyman, W.A., L.A. Masters, and S. Packard. 2016. The Universal Floristic Quality Assessment (FQA) Calculator: an online tool for ecological assessment and monitoring. Methods in Ecology and Evolution 7(3): 380-383

Herman, K.D., L.A. Masters, M.R. Penskar, A.A. Reznicek, G.S. Wilhelm, W.W. Brodovich, and K.P. Gardiner. 2001 floristic Quality Assessment with wetland categories and examples of computer applications for the State of Michigan - Revised, 2nd Edition. Michigan Department of Natural Resources, Wildlife, Natural Heritage Program, Lansing, MI. 19 pp. + appendices.

Horton, K.W. and Bedell, G.H., 1960. White and Red Pine ecology, silviculture and management.

Jolly, W.M., J. Hintz, R.L. Linn, R.C. Kropp, E.T. Conrad, R.A. Parsons, and J. Winterkamp. 2016. Seasonal variations in red pine (Pinus resinosa) and jack pine (Pinus banksiana) folia physio-chemistry and their potential influence on stand-scale wildland fire behavior. Forest Ecology and Management, Vol 373, p 167-178

Kimmerer, R.W., and F.K. Lake. 2001. The role of indigenous burning in land management. Journal of Forestry 99: 36–41.

Kost, M.A., D.A. Albert, J.G. Cohen, B.S. Slaughter, R.K. Schillo, C.R. Weber, and K.A. Chapman. 2007. Natural Communities of Michigan: Classification and Description. Michigan Natural Features Inventory Report Number 2007-21, Lansing, MI. 314 pp.

Kozlowski , T.T. and C. E. Ahlgren, 1974. Fire Ecology: Fire and Ecosystems. Eds. Academic Press, New York, xiv, 542 pp

Nowacki, G.J. and Abrams, M.D., 2008. The demise of fire and “mesophication” of forests in the eastern United States. BioScience, 58(2), pp.123-138.

Matthews, J.W., G. Spyreas, and C.M. Long. 2015. A null model test of Floristic Quality Assessment: Are plant species’ Coefficients of Conservatism valid? Ecological Indicators 52:1-7.

Michigan Library and Historical Center. Accessed February 2024. Notes from the internal lines survey of Presque Isle County, Michigan. Notes were compiled in 1851 by George H. Cannon. Interior Lines Collection number: Digital File: 15148. Surveyor Field Notes

Michigan Natural Features Inventory (MNFI). 1988. Draft criteria for determining natural quality and condition grades, element occurrence size-classes and significance levels for palustrine and terrestrial natural communities in Michigan. Michigan Natural Features Inventory, Lansing, MI. 39 pp.

Muzika, R.M., Guyette, R.P., Stambaugh, M.C. and Marschall, J.M., 2015. Fire, drought, and humans in a heterogeneous Lake Superior landscape. Journal of Sustainable Forestry, 34(1-2), pp.49-70.

NatureServe. 2024. NatureServe Explorer: An online encyclopedia of life [web application]. Version 7.1. NatureServe, Arlington, Virginia. Available http://explorer.natureserve.org. (Accessed: March 28, 2024).

Probst, J.R., 1988. Kirtland’s warbler breeding biology and habitat management. Integrating forest management for wildlife and fish, pp.28-35.

Probst, J.R. and Hayes, J.P., 1987. Pairing success of Kirtland’s Warblers in marginal vs. suitable habitat. The Auk, 104(2), pp.234-241.

Reznicek, A.A., M.R. Penskar, B.S. Walters, and B.S. Slaughter. 2014. Michigan Floristic Quality Assessment Database. Herbarium, University of Michigan, Ann Arbor, MI and Michigan Natural Features Inventory, Michigan State University, Lansing, MI. http://michiganflora.net

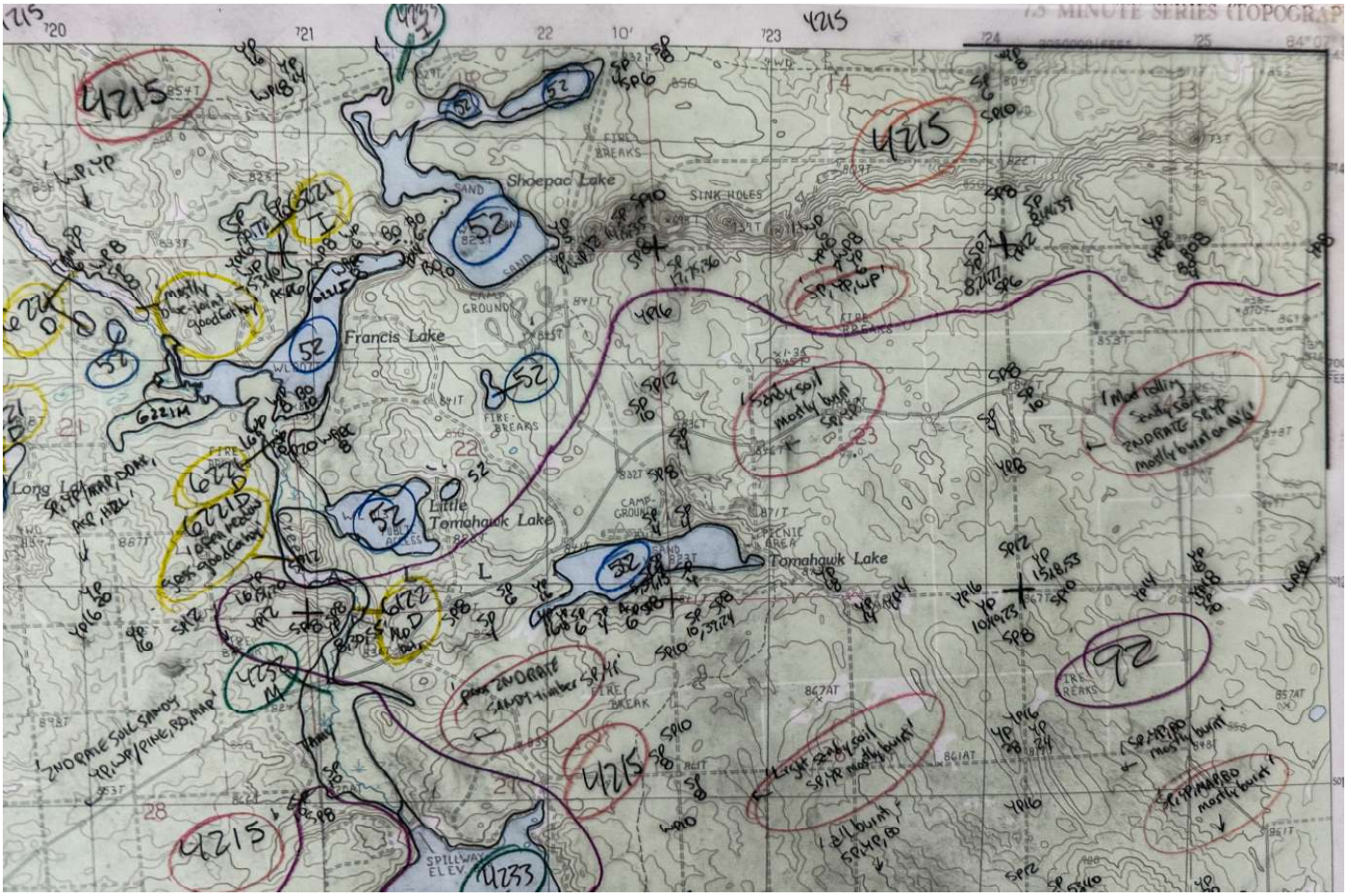
Scherer, S.S., D’Amato, A.W., Kern, C.C., Palik, B.J. and Russell, M.B., 2016. Long-term impacts of prescribed fire on stand structure, growth, mortality, and individual tree vigor in Pinus resinosa forests. Forest Ecology and Management, 368, pp.7-16.

Slaughter, B.S., A.A. Reznicek, M.R. Penskar, and B.S. Walters. 2015. Notes on the Third Edition of the Floristic Quality Assessment of Michigan. Wetland Science & Practice.

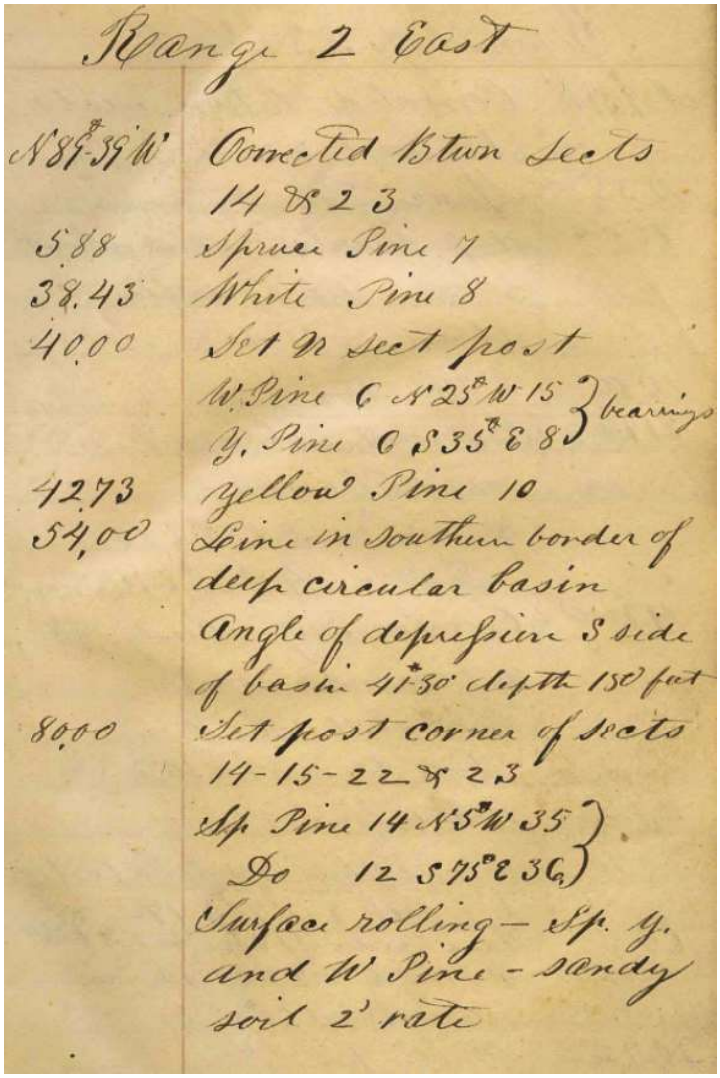
Stewart, O.C. 2009. Forgotten Fires: Native Americans and the Transient Wilderness. University of Oklahoma Press; Illustrated edition. 384 pp.

Sutheimer, C.M., Meunier, J., Hotchkiss, S.C., Rebitzke, E. and Radeloff, V.C., 2021. Historical fire regimes of North American hemiboreal peatlands. Forest Ecology and Management, 498, p.119561.

Appendicies



Appendix 1. Notes and tree sizes recorded in 1851 by George H. Cannon for the General Land Office were transcribed onto mylar topographic maps by MNFI. These notes and maps serve as the basis for the circa 1800 vegetation maps. 'YP' stands for yellow pine, the common name used for red pine (*Pinus resinosa*) at the time of the original surveys. 'SP' stands for spruce pine, the common name used for jack pine (*Pinus banksiana*) at the time of the original surveys.

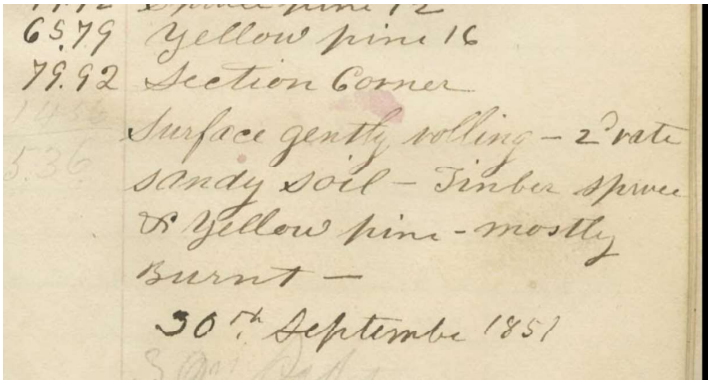


Range 2 East

N 87° 30' W	Corrected betwn Sects 14 & 23
5.88	Spruce Pine 7
38.43	White Pine 8
40.00	Set N sect post
	W. Pine 6 N 25° W 15 } bearings
	Y. Pine 6 S 35° E 8 }
42.73	Yellow Pine 10
54.00	Line in Southern border of deep circular basin
	Angle of depression S side of basin 41°30' depth 150 feet
80.00	Set post corner of Sects 14-15-22 & 23
	Sp. Pine 14 N 5° W 35 }
	Do 12 S 75° E 36 }
	Surface rolling — Sp. Y. and W Pine - sandy soil 2' rate

Transcribed Notes: Line in southern border of deep circular basin angle of depression S side of basin 41-30° depth 150 feet. Set post corner of sectios 14-15-22 & 23.

Surface rolling - sp, y, and w pine - sandy soil 2nd rate



65.79 Yellow pine 16
79.92 Section Corner
Surface gently rolling - 2nd rate sandy soil - Timber Spruce & Yellow pine - mostly Burnt —
30th September 1851

Transcribed Notes: yellow pine 16 (inch diameter)

Section corner, surface gently rolling - 2nd rate sandy soil - timber spruce & yellow pine - mostly burnt

30th September 1851

Appendix 2. Notes from George H. Cannon's 1851 surveys of the area around Tomahawk Sinkholes. Available through Michigan Library and Historical Center, Digital File: 15148.

Appendix 3. Species list for Tomahawk Pine Barrens.

Scientific Name	Common Name	Acronym	Native?	C	Physiognomy
Acer rubrum	red maple	ACERUB	native	1	tree
Amelanchier interior	serviceberry	AMEINT	native	4	shrub
Amelanchier sanguinea	round-leaved serviceberry	AMESAN	native	5	shrub
Andropogon gerardii	big bluestem	ANDGER	native	5	grass
Anemone cylindrica	thimbleweed	ANECYL	native	6	forb
Antennaria howellii	small pussytoes	ANTHOW	native	2	forb
Antennaria parlinii	smooth pussytoes	ANTPAL	native	2	forb
Apocynum androsaemifolium	spreading dogbane	APOAND	native	3	forb
Aquilegia canadensis	wild columbine	AQUCAN	native	5	forb
Aralia nudicaulis	wild sarsaparilla	ARANUD	native	5	forb
Arctostaphylos uva-ursi	bearberry	ARCUVA	native	8	shrub
Arenaria serpyllifolia	**thyme-leaved sandwort**	**ARESER**	**non-native**	**0**	**forb**
Artemisia campestris	wormwood	ARTCAM	native	5	forb
Asclepias syriaca	common milkweed	ASCSYR	native	1	forb
Asclepias tuberosa	butterfly-weed	ASCTUB	native	5	forb
Avenella flexuosa	hair grass	AVEFLE	native	6	grass
Boechera stricta	drummond rock cress	BOESTR	native	6	forb
Brachyelytrum aristosum	northern shorthusk	BRAARI	native	7	grass
Bromus kalmii	prairie brome	BROKAL	native	8	grass
Calystegia spithamaea	low bindweed	CALSPI	native	8	forb
Campanula rotundifolia	harebell	CAMROT	native	6	forb
Carex pensylvanica	sedge	CXPENS	native	4	sedge
Ceanothus herbaceus	new jersey tea	CEAHER	native	9	shrub
Centaurea stoebe	**spotted knapweed**	**CENSTO**	**non-native**	**0**	**forb**
Cirsium hillii	hills thistle	CIRHIL	native	8	forb
Clinopodium vulgare	wild-basil	CLIVUL	native	3	forb
Comandra umbellata	bastard-toadflax	COMUMB	native	5	forb
Comptonia peregrina	sweetfern	COMPER	native	6	shrub
Cornus foemina	gray dogwood	CORFOE	native	1	shrub
Corylus cornuta	beaked hazelnut	CORCOR	native	5	shrub
Crataegus schuettei	hawthorn	CRASCH	native	4	tree
Crataegus succulenta	hawthorn	CRASUC	native	5	tree
Crocanthemum canadense	common frostweed	CROCAN	native	8	forb
Dactylis glomerata	**orchard grass**	**DACGLO**	**non-native**	**0**	**grass**
Danthonia spicata	poverty grass; oatgrass	DANSPI	native	4	grass
Dichanthelium columbianum	panic grass	DICCOL	native	5	grass
Dichanthelium latifolium	broad-leaved panic grass	DICLAT	native	5	grass
Dichanthelium linearifolium	slender-leaved panic grass	DICLIE	native	4	grass
Dichanthelium xanthophysum	panic grass	DICXAN	native	6	grass
Diphasiastrum digitatum	ground-cedar	DIPDIG	native	3	fern
Elymus repens	**quack grass**	**ELYREP**	**non-native**	**0**	**grass**
Elymus trachycaulus	slender wheatgrass	ELYTRA	native	8	grass
Equisetum hyemale	scouring rush	EQUHYE	native	2	fern
Erigeron strigosus	daisy fleabane	ERISTR	native	4	forb
Euphorbia virgata	**leafy spurge**	**EUPVIR**	**non-native**	**0**	**forb**
Fallopia cilinodis	fringed false buckwheat	FALCIL	native	3	vine

Appendix 3, Continued. Species list for Tomahawk Pine Barrens.

Scientific Name	Common Name	Acronym	Native?	C	Physiognomy
Fragaria virginiana	wild strawberry	FRAVIR	native	2	forb
Galium aparine	annual bedstraw	GALAPA	native	0	forb
Gaultheria procumbens	wintergreen	GAUPRO	native	5	shrub
Gaylussacia baccata	huckleberry	GAYBAC	native	7	shrub
Helianthus divaricatus	woodland sunflower	HELDIV	native	5	forb
Hieracium aurantiacum	**orange hawkweed**	**HIEAUR**	**non-native**	**0**	**forb**
Hieracium caespitosum	**king devil**	**HIECAE**	**non-native**	**0**	**forb**
Hieracium gronovii	hairy hawkweed	HIEGRO	native	5	forb
Hieracium kalmii	kalms hawkweed	HIEKAL	native	3	forb
Hieracium scabrum	rough hawkweed	HIESCA	native	3	forb
Hieracium venosum	rattlesnake-weed	HIEVEN	native	6	forb
Hypericum perforatum	**common st. johns-wort**	**HYPPER**	**non-native**	**0**	**forb**
Lactuca canadensis	tall lettuce	LACCAN	native	2	forb
Lechea intermedia	intermediate pinweed	LECINT	native	6	forb
Liatris scariosa	northern blazing-star	LIASCA	native	5	forb
Lilium philadelphicum	wood lily	LILPHI	native	7	forb
Lithospermum caroliniense	plains puccoon	LITCAR	native	10	forb
Lonicera morrowii	**morrow honeysuckle**	**LONMOR**	**non-native**	**0**	**shrub**
Maianthemum canadense	canada mayflower	MAICAN	native	4	forb
Maianthemum racemosum	false spikenard	MAIRAC	native	5	forb
Malus coronaria	american crab	MALCOR	native	4	tree
Medicago lupulina	**black medick**	**MEDLUP**	**non-native**	**0**	**forb**
Melampyrum lineare	cow-wheat	MELLIN	native	6	forb
Monarda fistulosa	wild-bergamot	MONFIS	native	2	forb
Muhlenbergia mexicana	leafy satin grass	MUHMEX	native	3	grass
Oenothera biennis	common evening-primrose	OENBIE	native	2	forb
Oryzopsis asperifolia	rough-leaved rice-grass	ORYASP	native	6	grass
Packera paupercula	balsam ragwort	PACPAU	native	3	forb
Pedicularis canadensis	wood-betony	PEDCAN	native	10	forb
Pinus banksiana	jack pine	PINBAN	native	5	tree
Pinus resinosa	red pine	PINRES	native	6	tree
Pinus strobus	white pine	PINSTR	native	3	tree
Piptatherum pungens	rice-grass	PIPPUN	native	9	grass
Poa compressa	**canada bluegrass**	**POACOM**	**non-native**	**0**	**grass**
Poa pratensis	**kentucky bluegrass**	**POAPRA**	**non-native**	**0**	**grass**
Poa saltuensis	bluegrass	POASAL	native	5	grass
Polygala polygama	racemed milkwort	POLPOL	native	9	forb
Populus tremuloides	quaking aspen	POPTRE	native	1	tree
Potentilla simplex	old-field cinquefoil	POTSIM	native	2	forb
Prenanthes alba	white lettuce	PREALB	native	5	forb
Prunus americana	american wild plum	PRUAME	native	4	tree
Prunus pumila	sand cherry	PRUPUM	native	8	shrub
Prunus serotina	wild black cherry	PRUSER	native	2	tree
Prunus virginiana	choke cherry	PRUVIR	native	2	shrub
Pteridium aquilinum	bracken fern	PTEAQU	native	0	fern
Quercus alba	white oak	QUEALB	native	5	tree

Appendix 3, Continued. Species list for Tomahawk Pine Barrens.

Scientific Name	Common Name	Acronym	Native?	C	Physiognomy
Quercus ellipsoidalis	hills oak	QUEELL	native	4	tree
Quercus rubra	red oak	QUERUB	native	5	tree
Rhus aromatica	fragrant sumac	RHUARO	native	7	shrub
Ribes cynosbati	prickly or wild gooseberry	RIBCYN	native	4	shrub
Rosa blanda	wild rose	ROSBLA	native	3	shrub
Rubus allegheniensis	common blackberry	RUBALL	native	1	shrub
Rubus flagellaris	northern dewberry	RUBFLA	native	1	shrub
Rubus strigosus	wild red raspberry	RUBSTR	native	2	shrub
Salix humilis	prairie willow	SALHUM	native	4	shrub
Sanicula marilandica	black snakeroot	SANMAR	native	4	forb
Schedonorus arundinaceus	**tall fescue**	**SCHARU**	**non-native**	**0**	**grass**
Schizachne purpurascens	false melic	SCHPUP	native	5	grass
Schizachyrium scoparium	little bluestem	SCHSCO	native	5	grass
Securigera varia	**crown-vetch**	**SECVAR**	**non-native**	**0**	**forb**
Silene antirrhina	sleepy catchfly	SILANT	native	2	forb
Solidago hispida	hairy goldenrod	SOLHIS	native	3	forb
Solidago nemoralis	old-field goldenrod	SOLNEM	native	2	forb
Solidago speciosa	showy goldenrod	SOLSPE	native	5	forb
Symphoricarpos albus	snowberry	SYMALA	native	5	shrub
Symphyotrichum laeve	smooth aster	SYMLAE	native	5	forb
Symphyotrichum urophyllum	arrow-leaved aster	SYMURO	native	2	forb
Tanacetum vulgare	**garden tansy**	**TANVUL**	**non-native**	**0**	**forb**
Taraxacum officinale	**common dandelion**	**TAROFF**	**non-native**	**0**	**forb**
Thalictrum dasycarpum	purple meadow-rue	THADAS	native	3	forb
Toxicodendron rydbergii	poison-ivy	TOXRYD	native	3	shrub
Tragopogon dubius	**goats beard**	**TRADUB**	**non-native**	**0**	**forb**
Trifolium pratense	**red clover**	**TRIPRA**	**non-native**	**0**	**forb**
Trillium grandiflorum	common trillium	TRIGRA	native	5	forb
Vaccinium angustifolium	low sweet blueberry	VACANG	native	4	shrub
Viola adunca	sand violet	VIOADU	native	4	forb

Appendix 4. Conservation metrics for Tomahawk Pine Barrens.

Conservatism-Based Metrics:

Total Mean C:	3.8
Native Mean C:	4.5
Total FQI:	42
Native FQI:	45.9
Adjusted FQI:	41.5
% C value 0:	16.4
% C value 1-3:	27
% C value 4-6:	43.4
% C value 7-10:	13.1
Native Tree Mean C:	3.8
Native Shrub Mean C:	4.5
Native Herbaceous Mean C:	4.6

Species Richness:

Total Species:	122	
Native Species:	104	85.2%
Non-native Species:	18	14.8%

Species Wetness:

Mean Wetness:	3.5
Native Mean Wetness:	3.5

Physiognomy Metrics:

Tree:	13	10.7%
Shrub:	22	18.0%
Vine:	1	0.8%
Forb:	61	50.0%
Grass:	21	17.2%
Sedge:	1	0.8%
Rush:	0	0.0%
Fern:	3	2.5%
Bryophyte:	0	0.0%

Duration Metrics:

Annual:	5	4.1%
Perennial:	110	90.2%
Biennial:	7	5.7%
Native Annual:	3	2.5%
Native Perennial:	96	78.7%
Native Biennial:	5	4.1%

Appendix 5. Species consistently occurring in areas of high-quality pine barrens around the Tomahawk Sinkholes.

Scientific Name	Common Name	C	Physiognomy
Lithospermum caroliniense	plains puccoon	10	forb
Pedicularis canadensis	wood-betony	10	forb
Ceanothus herbaceus	new jersey tea	9	shrub
Piptatherum pungens	rice-grass	9	grass
Polygala polygama	racemed milkwort	9	forb
Arctostaphylos uva-ursi	bearberry	8	shrub
Bromus kalmii	prairie brome	8	grass
Calystegia spithamaea	low bindweed	8	forb
Cirsium hillii	hills thistle	8	forb
Crocanthemum canadense	common frostweed	8	forb
Elymus trachycaulus	slender wheatgrass	8	grass
Prunus pumila	sand cherry	8	shrub
Gaylussacia baccata	huckleberry	7	shrub
Lilium philadelphicum	wood lily	7	forb
Rhus aromatica	fragrant sumac	7	shrub
Anemone cylindrica	thimbleweed	6	forb
Avenella flexuosa	hair grass	6	grass
Boechera stricta	drummond rock cress	6	forb
Campanula rotundifolia	harebell	6	forb
Comptonia peregrina	sweetfern	6	shrub
Dichanthelium xanthophysum	panic grass	6	grass
Hieracium venosum	rattlesnake-weed	6	forb
Melampyrum lineare	cow-wheat	6	forb
Amelanchier sanguinea	round-leaved serviceberry	5	shrub
Andropogon gerardii	big bluestem	5	grass
Artemisia campestris	wormwood	5	forb
Asclepias tuberosa	butterfly-weed	5	forb
Comandra umbellata	bastard-toadflax	5	forb
Crataegus succulenta	hawthorn	5	tree
Dichanthelium columbianum	panic grass	5	grass
Helianthus divaricatus	woodland sunflower	5	forb
Hieracium gronovii	hairy hawkweed	5	forb
Liatris scariosa	northern blazing-star	5	forb
Poa saltuensis	bluegrass	5	grass
Schizachne purpurascens	false melic	5	grass
Schizachyrium scoparium	little bluestem	5	grass
Solidago speciosa	showy goldenrod	5	forb
Symphyotrichum laeve	smooth aster	5	forb
Danthonia spicata	poverty grass; oatgrass	4	grass
Prunus americana	american wild plum	4	tree
Salix humilis	prairie willow	4	shrub
Viola adunca	sand violet	4	forb
Hieracium kalmii	kalms hawkweed	3	forb
Hieracium scabrum	rough hawkweed	3	forb
Packera paupercula	balsam ragwort	3	forb
Solidago hispida	hairy goldenrod	3	forb
Prunus virginiana	choke cherry	2	shrub

Appendix 6. Species list for Tomahawk Dry-mesic Northern Forest.

Scientific Name	Common Name	Acronym	Native?	C	W	Physiognomy
Abies balsamea	balsam fir	ABIBAL	native	3	0	tree
Acer rubrum	red maple	ACERUB	native	1	0	tree
Adiantum pedatum	maidenhair fern	ADIPED	native	6	3	fern
Agrimonia gryposepala	tall agrimony	AGRGRY	native	2	3	forb
Amelanchier arborea	juneberry	AMEARB	native	4	3	tree
Apocynum androsaemifolium	spreading dogbane	APOAND	native	3	5	forb
Aquilegia canadensis	wild columbine	AQUCAN	native	5	3	forb
Aralia nudicaulis	wild sarsaparilla	ARANUD	native	5	3	forb
Arctium minus	**common burdock**	**ARCMIN**	**non-native**	**0**	**3**	**forb**
Brachyelytrum aristosum	northern shorthusk	BRAARI	native	7	5	grass
Carex deweyana	sedge	CXDEWE	native	3	3	sedge
Chimaphila umbellata	pipsissewa	CHIUMB	native	8	5	shrub
Clintonia borealis	bluebead-lily; corn-lily	CLIBOR	native	5	0	forb
Cornus canadensis	bunchberry	CORCAA	native	6	0	shrub
Cornus rugosa	round-leaved dogwood	CORRUG	native	6	5	shrub
Corylus cornuta	beaked hazelnut	CORCOR	native	5	3	shrub
Crataegus schuettei	hawthorn	CRASCH	native	4	5	tree
Crataegus succulenta	hawthorn	CRASUC	native	5	5	tree
Diervilla lonicera	bush-honeysuckle	DIELON	native	4	5	shrub
Dryopteris carthusiana	spinulose woodfern	DRYCAR	native	5	-3	fern
Epipactis helleborine	**helleborine**	**EPIHEL**	**non-native**	**0**	**0**	**forb**
Equisetum scirpoides	dwarf scouring rush	EQUSCI	native	7	0	fern
Eurybia macrophylla	big-leaved aster	EURMAC	native	4	5	forb
Galium aparine	annual bedstraw	GALAPA	native	0	3	forb
Gaylussacia baccata	huckleberry	GAYBAC	native	7	3	shrub
Hepatica americana	round-lobed hepatica	HEPAME	native	6	5	forb
Huperzia lucidula	shining clubmoss	HUPLUC	native	5	0	fern
Impatiens capensis	spotted touch-me-not	IMPCAP	native	2	-3	forb
Lonicera canadensis	canadian fly honeysuckle	LONCAN	native	5	3	shrub
Lonicera dioica	red honeysuckle	LONDIO	native	5	3	vine
Lycopus uniflorus	northern bugle weed	LYCUNI	native	2	-5	forb
Maianthemum canadense	canada mayflower	MAICAN	native	4	3	forb
Mycelis muralis	**wall lettuce**	**MYCMUR**	**non-native**	**0**	**5**	**forb**
Oryzopsis asperifolia	rough-leaved rice-grass	ORYASP	native	6	5	grass
Osmorhiza claytonii	hairy sweet-cicely	OSMCLI	native	4	3	forb
Pinus banksiana	jack pine	PINBAN	native	5	3	tree
Pinus resinosa	red pine	PINRES	native	6	3	tree
Pinus strobus	white pine	PINSTR	native	3	3	tree
Poa compressa	**canada bluegrass**	**POACOM**	**non-native**	**0**	**3**	**grass**
Poa saltuensis	bluegrass	POASAL	native	5	5	grass
Polygonatum pubescens	downy solomon seal	POLPUB	native	5	5	forb
Populus grandidentata	big-tooth aspen	POPGRA	native	4	3	tree
Populus tremuloides	quaking aspen	POPTRE	native	1	0	tree
Prenanthes alba	white lettuce	PREALB	native	5	3	forb
Prunus nigra	canada plum	PRUNIG	native	4	3	tree
Prunus virginiana	choke cherry	PRUVIR	native	2	3	shrub
Pteridium aquilinum	bracken fern	PTEAQU	native	0	3	fern
Pyrola americana	round-leaved pyrola	PYRAME	native	7	0	forb
Quercus alba	white oak	QUEALB	native	5	3	tree
Quercus rubra	red oak	QUERUB	native	5	3	tree

Appendix 6, continued. Species list for Tomahawk Dry-mesic Northern Forest.

Scientific Name	Common Name	Acronym	Native?	C	W	Physiognomy
Ribes cynosbati	prickly or wild gooseberry	RIBCYN	native	4	3	shrub
Rosa blanda	wild rose	ROSBLA	native	3	3	shrub
Rubus flagellaris	northern dewberry	RUBFLA	native	1	3	shrub
Rubus pubescens	dwarf raspberry	RUBPUB	native	4	-3	shrub
Salix humilis	prairie willow	SALHUM	native	4	3	shrub
Sanicula odorata	black snakeroot	SANODO	native	2	0	forb
Symphoricarpos albus	snowberry	SYMALA	native	5	3	shrub
Symphyotrichum urophyllum	arrow-leaved aster	SYMURO	native	2	5	forb
Toxicodendron rydbergii	poison-ivy	TOXRYD	native	3	0	shrub
Trillium grandiflorum	common trillium	TRIGRA	native	5	3	forb
Vaccinium angustifolium	low sweet blueberry	VACANG	native	4	3	shrub
Vaccinium myrtilloides	canada blueberry	VACMYR	native	4	-3	shrub
Viburnum acerifolium	maple-leaved viburnum	VIBACE	native	6	5	shrub
Viola blanda	sweet white violet	VIOBLA	native	5	-3	forb
Viola labradorica	dog violet	VIOLAB	native	3	0	forb

Appendix 7. Conservation metrics for Tomahawk Dry-mesic Northern Forest.

Conservatism-Based Metrics:

Total Mean C:	3.9
Native Mean C:	4.2
Total FQI:	31.4
Native FQI:	32.8
Adjusted FQI:	40.7
% C value 0:	9.2
% C value 1-3:	24.6
% C value 4-6:	58.5
% C value 7-10:	7.7
Native Tree Mean C:	3.8
Native Shrub Mean C:	4.5
Native Herbaceous Mean C:	4.2

Species Richness:

Total Species:	65	
Native Species:	61	93.80%
Non-native Species:	4	6.20%

Species Wetness:

Mean Wetness:	2.3
Native Mean Wetness:	2.3

Physiognomy Metrics:

Tree:	13	20%
Shrub:	18	27.70%
Vine:	1	1.50%
Forb:	23	35.40%
Grass:	4	6.20%
Sedge:	1	1.50%
Rush:	0	0%
Fern:	5	7.70%
Bryophyte:	0	0%

Duration Metrics:

Annual:	2	3.10%
Perennial:	61	93.80%
Biennial:	2	3.10%
Native Annual:	2	3.10%
Native Perennial:	59	90.80%
Native Biennial:	0	0%