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Conservation Issues

Riverscour Ecosystems of Eastern Unglaciated North America: A Review

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ABSTRACT

Riverscour is an eclectic assemblage of highly biodiverse riparian natural communities that share characteristics with grasslands, savannas, glades, wetlands, and floodplains. We define "riverscour" as "open riparian habitats of rocky, stable-substrate (bedrock, boulder, cobble) zones, often along high-gradient streams, where periodic high-energy flows (water, ice, debris) and edaphic factors inhibit woody vegetation and promote persistent grassland-shrubland-open woodland-outcrop communities rich in conservative heliophytes." A key factor distinguishing riverscour from gravel and sand bars and other floodplain habitats is that these areas are underlain by more stable substrates, which resist structural reworking by floodwaters. Within Eastern Unglaciated North America, we mapped 1322 stream reaches totaling 2385.8 km containing riverscour. Given their small size, these communities support a disproportionately large number of rare, endemic, and undescribed species. For example, within a five-county area in Tennessee, riverscour makes up significantly less than 1% of the area but contributes at least 37 (25%) of the region's 150 state- and federally-listed vascular plant species. There are numerous threats to riverscour, the greatest being inundation caused by impoundment of rivers and associated downstream hydrologic alterations. Interruption of scouring processes associated with flooding and/or ice promotes succession toward larger woody species and away from open herbaceous/shrub-dominated vegetation. Other threats include invasive species, recreation pressure, and climate change. These threats, coupled with high biodiversity and historical losses, make protection and proper management of riverscour ecosystems especially important in conserving the native biodiversity of eastern North America.

Index terms: boulder bars; cobble bars; flood-maintained; riparian; riverscour grasslands

INTRODUCTION

Most 20th-century ecologists considered forests to be the predominant natural pre-settlement vegetation of eastern temperate North America (Braun 1950; Küchler 1965). Braun believed this "endless expanse of forest" to be broken only "by swamps and bogs, by cliffs and river bluffs…, by windfalls and burns, [and] by small grassy openings…."

In the 21st century, there has been increasing recognition that topographically dissected landforms and extensive floodplains were, and in some cases still are, heavily forested, whereas flatter to rolling landscapes often supported more open ecosystems at the time of European settlement (the 1500s–1800s; Hanberry and Noss 2022). Many of these open landscapes are collectively grouped under a broad umbrella of "grasslands" (Noss 2012; Noss et al. 2021). These include a range of habitats, from treeless prairies to salt marshes, small glades and meadows, to expansive, sparsely treed savannas. Many of these communities were historically maintained by fire, grazing, and/or edaphic conditions (Anderson et al. 1999; Noss 2012).

Riverscour is an often overlooked and poorly understood grassland system found within river and stream floodplains in mountainous or hilly regions. These communities are maintained by high-energy floods and/or scouring by winter ice, in combination with edaphic factors. Within Eastern Unglaciated North America (EUNA), riverscour communities are scattered across upland physiographic provinces from Georgia and Texas to Pennsylvania. While there have been studies of other types of open ecosystems in EUNA (e.g., prairies, glades, cliffs), limited studies have focused on riverscour biodiversity, ecology, and conservation.

Riverscour habitats are often dominated or co-dominated by warm-season grasses, including *Andropogon gerardii*, *Panicum virgatum*, *Schizachyrium scoparium*, *Sorghastrum nutans*, and *Tripsacum dactyloides*. There are also diverse assemblages of forbs (*Amsonia* spp., *Baptisia* spp., *Coreopsis* spp., *Eupatorium* spp., *Euphorbia* spp., *Solidago* spp., *Symphyotrichum* spp., *Tephrosia virginiana*) and shrubs characteristic of open habitats such as *Alnus serrulata*, *Amorpha fruticosa*, *Cephalanthus occidentalis*, *Chionanthus virginicus*, *Cornus amomum*, *Hamamelis vernalis*, *Hypericum prolificum*, *Ilex verticillata*, *Itea virginica*, *Lyonia ligustrina*, *Physocarpus opulifolius*, *Rhododendron periclymenoides*, *Salix caroliniana*, *Vaccinium* spp., *Viburnum* spp., and *Yucca flaccida*. Saplings or stunted specimens of trees are often common and may include *Betula nigra*, *Carpinus caroliniana*, *Diospyros virginiana*, *Juniperus virginiana*, *Nyssa* *sylvatica*, *Pinus virginiana*, and *Platanus occidentalis*. Throughout this manuscript we follow the taxonomic nomenclature of *Flora of the Southeastern United States* (Weakley and the Southeastern Flora Team 2022).

Riverscour habitats (hereinafter simply "riverscour") harbor species adapted to riverine ecosystems (periodic flooding), wetlands (frequently saturated soils), and upland grasslands and woodlands (droughty shallow, sandy, or rocky soils; increased insolation and temperature). Fire and grazing, the factors responsible for maintaining many grassland–open woodland systems, are thought to be of limited importance in riverscour ecology due to their entrenched landscape position, adjacency to streams, and rockiness. Edaphic factors (shallow, rocky, or sandy soils) and the physical disturbance caused by high-velocity floodwaters and winter ice are essential factors in maintaining riverscour vegetation.

Scour communities (Figure 1) exist as small-patch or linear systems diverse in structure and appearance, including prairie-like grasslands, shrublands, woodlands, sparsely vegetated bedrock glades, outcrops, and barrens. Common communities within river floodplains, such as in-channel riverine/riverbed habitats and backwater or channel scar emergent wetlands, shorelines, and seepage wetlands, are closely associated with riverscour habitats. Forested or wooded communities are almost always adjacent, where the processes that maintain riverscour are too infrequent or muted to inhibit woody plant encroachment.

The relative stability of open riverscour ecosystems over long periods (Wolfe et al. 2007) leads to them serving as dependable refugia for conservative heliophytic (sun-loving) species. Their stability has led to the evolution of endemic species found only, or primarily, in riverscour. These ecosystems also frequently support numerous species that are rare and/or disjunct between ecoregions.

It is imperative to synthesize information about riverscour while these ecosystems remain relatively intact. Many rare and endemic species exist in these habitats (Estill and Cruzan 2001; Cartwright 2019), including several apparently undescribed species needing study and description (Weakley and the Southeastern Flora Team 2022). Their high species richness and diversity, coupled with historical losses and degradation of many riverscour systems from dam construction, hydrologic alterations, invasive species, recreation, and other factors, make riverscour systems especially important in conserving the native biodiversity of eastern North America.

In this article, we (1) define the term riverscour for EUNA, (2) review the evolution of knowledge of these systems over time, (3) describe their biophysical characteristics, (4) map known occurrences, (5) assess their ecological significance, (6) discuss their biogeography, (7) illuminate key threats, (8) address their relevance to conservation, and (9) emphasize potential areas for future research. This study represents an early attempt to understand and summarize the basic ecology and biodiversity of, and threats to, an entire ecosystem across its geographic range. We realize this is a lofty goal, but it is a critical step in conservation that is seldom accomplished.

Definition of Riverscour Ecosystems

Currently there is no widely accepted inclusive term for open riparian areas subject to high-velocity floodwaters and/or ice scour, AND that possess a diverse assemblage of upland, wetland, and heliophytic plants. We propose adoption of the following definition, adapted from the many published assessments of local sites across EUNA:

> "Open riparian habitats of rocky, stable-substrate (bedrock, boulder, cobble) zones, often along high-gradient streams, where periodic high-energy flows (water, ice, debris) and edaphic factors inhibit woody vegetation and promote persistent grassland-shrubland-open woodland-outcrop communities rich in conservative heliophytes."

We recognize that there are many scoured areas within river and stream channels and floodplains. Many floodplain ecosystems are inherently "scoured." However, this disturbance alone does not define riverscour. In the following sections, we will further explore the defining characteristics of riverscour, often using other more common communities/assemblages within the river floodplain as subjects of comparison. We also recognize that our investigation into riverscour focuses on the plants that make up these communities. Future research should consider other organisms that depend on these ecosystems.

History of the Recognition and Study of Riverscour

One of the earliest references to riverscour in North America is Charles W. Short's letter to John Torrey and Asa Gray describing one riverscour endemic species, the extinct *Orbexilum stipulatum* and the federally endangered riverscour near-endemic, *Solidago shortii*, from the Falls of the Ohio River near Louisville, Kentucky. Short (1842) writes: "They occupy almost exclusively a tract of rocky waste which is submerged for half the year, during which time it is swept over by a furious current, under which no plant could maintain a footing but by sticking its roots deep into the fissures in the rocks." A few decades later, on Pennsylvania's Youghiogheny River, Shafer (1905) vividly describes riverscour: "[The river] traverses a series of mad rapids, the rock banks of which are frequently inundated for short periods. The sandy pockets of these banks are exceedingly rich in plants, many of them of great interest and often of southern affinities."

At the start of the 20th century, Kearney (1900) referred to unique pine savanna-like riparian communities from the floodplains of the French Broad and Hiwassee rivers of Tennessee and the Little River of Lookout Mountain, Alabama, rich in herbaceous species typical of Coastal Plain pine savannas. Early ecologists do not appear to have used the term "riverscour" even as they wrote about endemic species found only in scour zones. For example, Jennison (1933) described the endemic *Conradina verticillata* from "sandy beaches," and Braun (1936) noted this species as occurring "locally along the banks of the South Fork of the Cumberland River" in Kentucky, but neither used the term riverscour or elaborated on the distinctiveness of these flood-maintained communities.

In West Virginia, Core (1966) described "rocky riverbanks" characterized by *Ionactis linariifolia*, *Solidago racemosa*, and *Marshallia pulchra* on the Tygart Valley River and noted similar vegetation along the Cheat, Potomac, and Gauley Rivers. Bush (1976) described a "prairie-like situation" along the Tygart Valley River, and discussed the importance of heat, drought, and flooding to maintain the unusual vegetation. From the 1980s to

Figure 1.—Representative photographs of riverscour communities of Eastern Unglaciated North America (EUNA), arranged from northeast to southwest (see Figure 2). Selected photos show the range of variation in stream size, substrate, and vegetation cover found throughout the region. These photos also depict the range of physiognomic conditions encountered, including open, sparsely vegetated bedrock zones, perennial grass- and forb-dominated grasslands, saturated or inundated wetlands, shrublands, and open woodlands. Sites include (a) Susquehanna R., PA; (b–c) Youghiogheny R., PA; (d) Great Falls of the Potomac R., MD; (e) Potomac R., MD; (f) Gauley R., WV; (g) Ohio Brush Fork, OH; (h) Big South Fork of the Cumberland R., TN; (i–j) Clear Fork, TN; (k) Daddys Creek, TN; (l–m) Caney Fork, TN; (n) Hiwassee R., TN; (o) East Fork Little River, AL; (p) Locust Fork of the Black Warrior R., AL; (q) East Fork Black R., MO; (r–t) South Fourche LaFave R., AR; (u) Irons Fork of the Ouachita R., AR; (v) Cossatot R., AR; (w–x) Guadalupe R., TX. Photo credits: Mason Brock (l, p), Todd Crabtree (s), Adam Dattilo (n), Dwayne Estes (i, j, k, m, o), Chris Mausert-Mooney (h), Reed Noss (e, g), Jason Singhurst (w, x), Christopher Tracey (a, b, c), Jim Vanderhorst (d, f), Theo Witsell (r, t, u, v), Kbh3rd, CC BY 3.0 <https://creativecommons.org/licenses/by/3.0>, via Wikimedia Commons (q, photo cropped from original panorama).

Figure 1.—Continued.

2000, riverscour habitats along the Shenandoah, Potomac, Cheat, Tygart Valley, Buckhannon, Gauley, and New Rivers were a focus of rare plant surveys and ecological studies by the West Virginia Natural Heritage Program (WVDNR 2022; unpublished reports cited in Vanderhorst 2007). In nearby Pennsylvania, Fike (1999) described a "Riverside Ice Scour Community" from the Youghiogheny River, later revised as "Floodplain Scour Community" (Zimmerman 2011).

Figure 1.—Continued.

Figure 1.—Continued.

In the Cumberland Plateau of Tennessee, botanist Albert Ruth was among the earliest to collect specimens from riverscour in 1884 (Shea and Roulston 1996). About 50 y later, in the 1930s–1940s, H.M. Jennison, A.J. Sharp, and J.K. Underwood again visited riverscour habitats to collect herbarium specimens (SERNEC 2022). They used descriptors such as "sandy flood plains," "sandy beach," "clear sandy shore," "sand on low bank," "rocky and sandy soil." Later, proposals to impound numerous rivers in the eastern U.S. led to more focus on environmental impact studies and the listing of some species under the Endangered Species Act (1973), which ignited inventory and monitoring efforts by university and agency biologists (Patrick 1979; Patrick and Wofford 1981; Schmalzer and DeSelm 1982). These later visitors to riverscour described them as "bar," "boulder-cobble bar," "cobble bar," "river bar," and "rocky river bar" (SERNEC 2022). Schmalzer and DeSelm (1982) noted one of the major non-forest vegetation types of the Obed Wild and Scenic River was a "riparian shrub-herb type on gravel bars and sand bars adjacent to the river." They described these as supporting "shrub-thickets, characterized by shrubs and shrub-size individuals [of tree species]" with "more open areas occupied by perennial grasses, small shrubs, and herbs ... maintained by periodic flooding." Most of the interest in riverscour was on the vascular flora of these specialized riparian communities (Schmalzer et al. 1985; Bailey and Coe 2001). In recent years, a series of graduate student theses and related studies have been dedicated to studying the flora and vegetation associations of riverscour in the Cumberland Plateau across Alabama, Kentucky, and Tennessee (Anderson 2016; Rodgers 2016; Brock 2017; Irick et al. 2023). Yahn (n.d.) highlighted what he called unique "river-scour bars" of Kentucky's portion of the Cumberland Plateau.

In the Interior Plateau ecoregion, Pyne and Withers (1996) described a scoured riverine bluff prairie community on bluffs and bedrock shelves of Tennessee's Duck River and similar situations on Kentucky's Green and Kentucky Rivers (Cartwright and Wolfe 2016). Homoya and Abrell (2005) referred to a similar Interior Plateau limestone-scour community along Indiana's Blue River with four descriptors: "brush prairie gravel wash," "scour prairie," "riverwash bedrock prairie," and "riverledge limestone pavement."

Riverscour habitats of the western areas of our study region are comparatively poorly known. In the Interior Highlands ecoregion, Nelson (2005) nested riverscour communities of Missouri under two general categories, "gravel wash" and "streambank/riverbank," where they may be associated with "shut-ins," sections of rivers in the St. Francois Mountains where a river is hemmed-in by erosion-resistant igneous rock that creates exposed bedrock outcrops in the channel. These communities meet our definition of riverscour in that conservative heliophytes prevail. However, the more abundant and dynamic gravel bar communities found in the area are often dominated by weedy, non-conservative species, and are not considered riverscour. In Arkansas, riverscour has been documented on multiple rivers across the Ouachita Mountains, Arkansas Valley, Boston Mountains, and Ozark Plateaus ecoregions, but these communities remain poorly described. In Oklahoma, riverscour vegetation along the Blue River in the Cross Timbers ecoregion was classified as "cobble bars," according to Hoagland (2000). Yet little has been written about riverscour communities in eastern Oklahoma's Ouachita Mountains. Habitats on early collections of the Ouachita Mountain riverscour endemics *Amsonia hubrichtii* and *Vernonia lettermanii* were variously given as "rocky creek-bottoms," "rocks in creek-bottoms," "rocky creek-beds," "gravelly flood-plain bed of river," "along bed of rocky branch," "bed of dry rocky creek," "shale outcrop subject to overflow," "gravel bars," "river banks," "ripples in novaculite rock," "rocky ledges on high river banks," and "on gravel and shingle of creek bed" (Gray 1880; Woodson 1943; SERNEC 2022). In the far western portion of our study area, in the Edwards Plateau ecoregion of Texas, riverscour vegetation has been described with such terms as "periodically scoured flat-bedded limestone shores of perennial streams" or as "stream-scoured grassland" from the North Fork of the Guadalupe River (Singhurst et al. 2010).

Riverscour communities north of the glacial maximum have also been described for northeastern and Great Lakes states, including Connecticut, Illinois, Maine, Massachusetts, New Hampshire, New Jersey, New York, and Vermont (NatureServe 2022), as well as in Alaska, the Rocky Mountains, and Canada (Westervelt et al. 2006; Rood et al. 2007; Mouw et al. 2013).

DeSelm (1992, 1994) may have been the first to classify riverscour vegetation as grasslands, including them within his concept of the "barrens" of Tennessee, noting them to be "brushy" and flood-maintained. Noss (2012) also included riverscour in his book, *Forgotten Grasslands of the South*, as did Estes et al. (2016) in *A Guide to Grasslands of the Mid-South*.

The compound word "riverscour" was probably first coined and used in unpublished reports in the 1990s, but the first published usage of the term to denote these systems appears to be NatureServe's description of the Cumberland Riverscour Ecological System (Comer et al. 2003). In another early use, Mahan (2004), in a technical report concerning the New River Gorge of West Virginia, uses "riverscour" in map captions.

Biophysical Characteristics of Riverscour

It is unclear why characteristic riverscour vegetation is limited to particular sites within the scour zones of floodplains. In these settings, sparsely vegetated jumbles of boulders and cobbles grade sharply into riparian forests, but the open flood-prone zones lack conservative heliophytes. Explanations to account for the lack of riverscour could be due to a lesser degree of insolation related to canyon width and depth, canyon orientation relative to the sun, steepness of the river channel, or other factors. The presence of riverscour vegetation could also be due to the proximity of other grassland systems which have served to supply riverscour communities during past and present epochs, as opposed to scour zones embedded in regions almost entirely dominated by forests. Few studies have focused on the geophysical characteristics of riverscour or the role of hydrology in shaping these communities (Wolfe et al. 2007; Cartwright and Wolfe 2016). The following summarizes the current state of knowledge of their geographical distribution and geophysical characteristics.

Geographic Distribution within EUNA: Cartwright and Wolfe (2016) provided a list of rivers with riverscour

Table 1.—Notable streams with riverscour habitat by state within Eastern Unglaciated North America. Length of the river is based on mapping presented in Figure 2.

State	# Rivers	Total length (km)	Example rivers
AL	5	57.1	Little Cahaba R., Little R., Locust Fork (of the Black Warrior R.), Mulberry Fork (of the Black Warrior R.), Tennessee R.
AR	54	644.6	Cossatot R., Big Piney Cr., Ouachita R., South Fourche LaFave R., Rolling Fork (of the Little River)
DC	1	1.9	Potomac R.
GA	3	12.1	Chattooga R., Flint R., Rock Cr.
IN	3	21.7	Blue R., Rock Cr., Ohio R.
KY	14	260.3	Big South Fork (of the Cumberland R.), Buck Cr., Green R., Kentucky R., Little South Fork (of the Cumberland R.), Ohio R., Rockcastle R.
MD	2	25.3	Potomac R., Shenandoah R.
MO	1	3.3	East Fork Black R.
NC	2	16.3	Nolichucky R., Yadkin R.
NJ	1	80.9	Delaware R.
NY	1	12.4	Delaware R.
OH	1	11.3	Ohio Brush Fork, Ohio R.
OK	12	97.6	Blue R., Caney Cr., Glover R., Kiamichi R., Little R., Mountain Fork
PA	11	297.0	Allegheny R., Susquehanna R., Youghiogheny R.
TN	17	217.2	Big South Fork (of the Cumberland R.), Caney Fork, Clear Cr., Clear Fork, Cumberland R., Daddys Cr., Duck R., Emory R., Hiwassee R., New R., Obed R., Ocoee R., Whites Creek
TX	8	76.0	Colorado R., Frio R., Guadalupe R., Llano R., Pedernales R.
VA	8	53.0	James R., Maury R., Potomac R.
WV	30	580.0	Buckhannon R., Cacapon R., Cheat R., Gauley R., Greenbrier R., Middle Fork R., New R., Shenandoah R., Tygart Valley R.

communities in the southeastern U.S. east of the Mississippi River and south of the Ohio-Potomac. These and others we have added are listed in Table 1 and mapped in Figure 2. A few streams with known riverscour to the north (e.g., Delaware River) and west (Pedernales River) of our study area boundary are also mapped since they either flow into our study area or are tributaries to streams that enter our area. Comprehensive and systematic mapping and study of riverscour ecosystems have yet to be completed. We map riverscour habitat for 18 states plus the District of Columbia. Within our EUNA focal region, which includes all or parts of 24 states, Delaware, Florida, Illinois, Kansas, Louisiana, and Mississippi did not have any identified riverscour.

Distribution Patterns within a Given Stream: On second- and higher-order streams, riverscour habitats may form discrete patches or occupy continuous linear zones (Cartwright and Wolfe 2016). Individual riverscour patches vary in size from <1 to 38 ha. Most are mapped within 20 m of the river channel (NPS 2016a). Individual riverscour patches may occur as discrete alluvial bars separated by tens of meters to many kilometers. On the Obed River, Wolfe et al. (2007) documented 201 separate bars over 69 km with an average of three bars per kilometer. Rarely, riverscour zones may be quite expansive and occupy continuous reaches of the entire riverbed along a few kilometers, such as at the Great Falls of the Potomac River. Historically, the Muscle Shoals of north Alabama on the Tennessee River may have been more extensive, where the river cut through beds of chert over a distance of ~25 km, but these were destroyed by inundation following the completion of Wilson Dam in 1924. Along other streams, such as Kentucky's Buck Creek, narrow scour zones only a few meters wide may occur as long, linear ledges or rocky shores for hundreds of meters in length. On others, such as Indiana's Blue River, scour communities are naturally limited to just one or a few places. On rivers with more discrete scour patches, Wolfe et al. (2007) provided morphometrics for three boulder bars, ranging from 58 to 100 m long and 32 to 46 m wide.

Riverscour habitats can occur through various settings of the river corridor, including straight to curving reaches, on the outsides or insides of bends, on point bars, or in association with rapids and falls. Knickpoints in the channel created by bedrock outcrops, such as at falls and rapids, also are common places for riverscour (Brock 2017; Vanderhorst 2017). They may be associated with shallowly to deeply entrenched gorges where high-gradient rivers downcut through plateaus or escarpments, or cut through mountain ranges. Riverscour may also occur on streams that lack entrenched gorges or strong gradients but where stream morphology and the presence of exposed bedrock amplify scouring effects, such as where a stream flows against bedrock on outside bends (Pyne and Withers 1996; Homoya and Abrell 2005; Cartwright and Wolfe 2016).

Fluvial Geomorphology: The forces of scour and fill, important fluvial processes related to stream energy during floods, combined with complex fluvial landforms, stream morphology, and substrate, dictate the community structure of riverscour ecosystems. Leopold et al. (1964) defined "scour" as the short-term (single event) process of removal of sediment from a stream's bed, resulting from increased water velocities and shear-stress on the surface, whereas "fill" is the short-term process of sediment deposition from a river's bed-load onto a fluvial surface (Lea 2000). These processes unite to create the open, high-sunlight structure of scour corridors, harsh edaphic and extreme hydrologic conditions, and sediment deposition needed to support the rich assemblage of riverscour vegetation and species.

Riverscour communities occur in association with a variety of landforms. For example, riverscour occurs in association with alluvial fans, blocky mantles, bouldery floodplains, colluvial

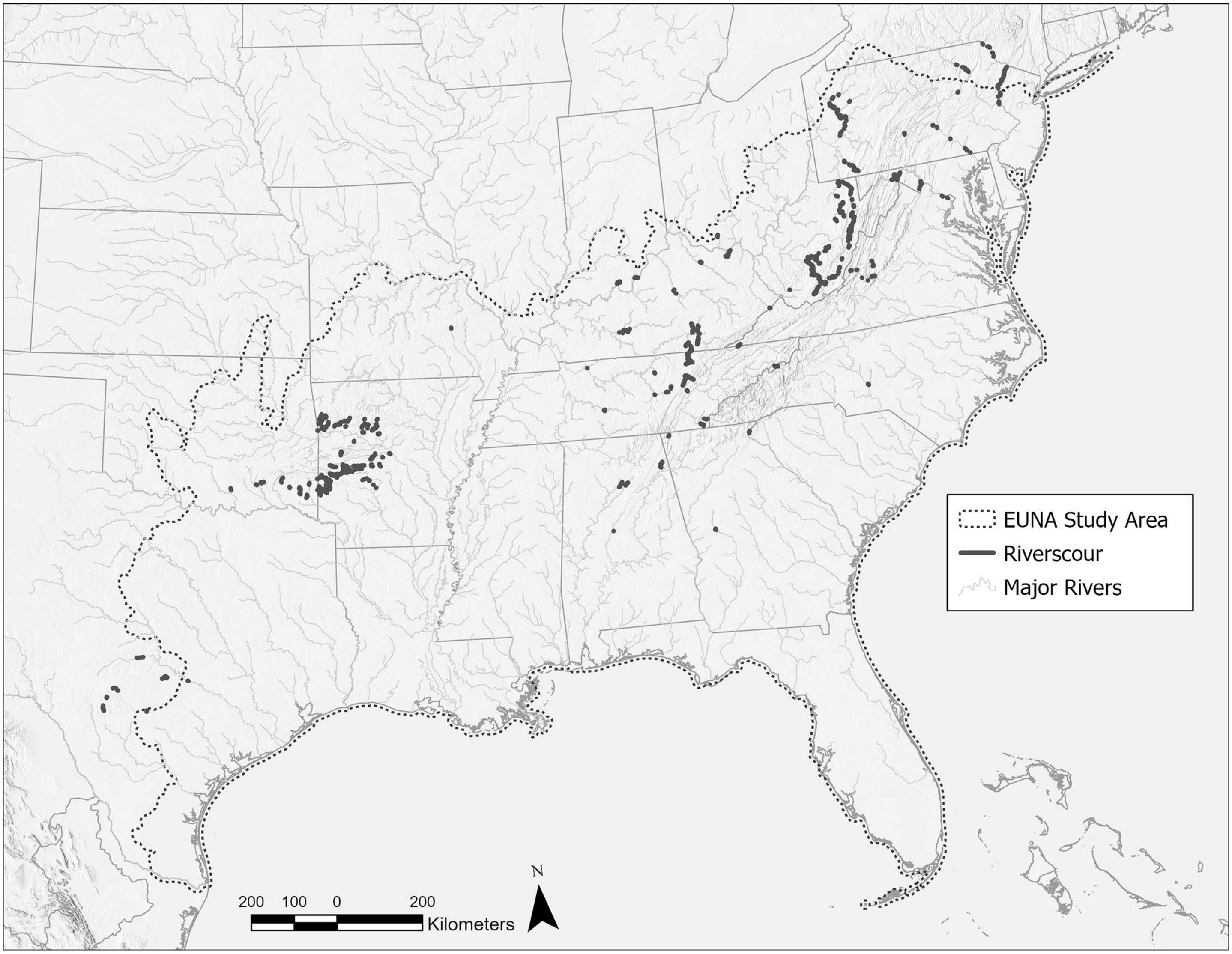

Figure 2.—Distribution of known riverscour habitats of Eastern Unglaciated North America (EUNA). A few rivers with riverscour that occur just outside our boundary are also shown because they occur along streams that flow into our EUNA study area.

aprons, entrenched stream channels, river channels, rock-floored floodplains, and terraces. Side tributaries may introduce additional bed loads of cobble and boulder into the main stem of a river forming unconsolidated bars. Along some rivers, possible evidence of ancient (possibly Pleistocene), elevated scours located outside of the flood zone have been observed and appear as small, open sand barrens embedded within adjacent slope forests (Anderson 2016; Brock 2017).

Geology: Riverscour habitats form on a variety of rock types. Those over igneous (rhyolite) or metamorphic (gneiss, meta-graywacke, phyllite, schist) bedrock have exposed bedrock outcrops. Sandstone riverscour include bedrock outcrops and unconsolidated bars of smooth rounded boulders or cobbles with interstitial areas filled with sand. Limestone, chert, or dolostone riverscour form along exposed horizontally bedded glade-like ledges or shelves, or form jumbles of sharp-edged boulders, with clayey or marly deposits. Some rivers in the Ouachita Mountains and some tributaries in the Potomac drainage have scour zones developed primarily over shale that lack boulder or cobble development. In most cases, riverscour communities within a single river system occur on one geologic substrate, but in some cases, several unique riverscour communities may form on a single river as the river downcuts through distinct geologies.

Substrate Stability: One key factor distinguishing riverscour from gravel and sand bars is a more stable substrate, which resists structural reworking by periodic flood events. Wolfe et al. (2007) concluded that riverscour bars of boulder and cobble are highly stable judging from comparisons of modern and historical photographs. Alluvial boulders aggregate into imbricated alluvial bars, forming where sediment-laden flow loses power (e.g., stream confluences, eddies, bends) (Wolfe et al. 2007). Over time, bars increase in height as new boulders and cobbles accumulate, affecting bar topography and morphology. Scour glades developed over bedrock exposures are the most structurally stable of all riverscour habitats.

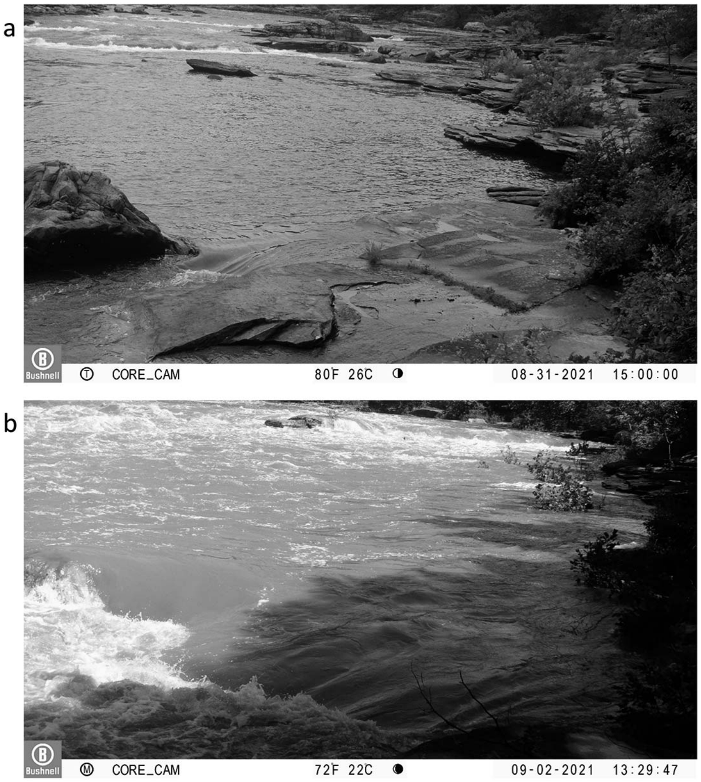

Figure 3.—Bedrock riverscour habitat at the Youghiogheny River near Ohiopyle, PA during (a) low-flow conditions (1070 cfs) and (b) scouring conditions (8750 cfs). Discharge rates as measured by USGS gage 03081500, just upstream of this site.

According to Hupp (1983), strength of disturbance (frequency and depth of flooding, frequency and intensity of scouring) is proportional to the distance from the stream center, forming a gradient from the thalweg to the edge of a scour bar. This relationship determines the distribution of particle sizes in the channel and along stream margins, with boulders predominating within the active channel, giving way to mixes of boulder and cobble farther away, and often with sand carrying farthest shoreward. This pattern is idealized and is generally more complex due to variations in stream geology, size, and structure. This complexity is increased by the contribution of non-alluvial boulders from mass-wasting of upslope cliffs and debris slides (Wolfe et al. 2007).

Topography: The arrangement of sediments may be correlated to the vegetation associations on individual scour bars. Boulders, cobble bars, bedrock exposures, and other features form topographic variations within riverscour zones that affect scouring intensity (Wolfe et al. 2007). Individual bars are usually elevated, 0.9–1.5 m (Wolfe et al. 2007), or occur at or less than 1 m above summer base-flow of streams, but some types, such as the Potomac River Gorge Riverside Outcrop Barren in Maryland and Virginia or riverside limestone glades of Tennessee's Caney Fork River, may be elevated 5–10 m above summer base-flow. Some scour zones are very heterogeneous microtopographically. Microtopography patterns determine the length and depth of inundation. Topographic highs, flooded only by exceptional floods, may be sparsely vegetated rocky promontories with scattered xerophytes. In contrast, topographic lows may flood more frequently and sometimes support vernal pools and wetlands with hydrophytes.

Hydrology: The power of floods to create and maintain riverscour habitats is shown by before and after photography (Figure 3). Flow rates for streams vary based on watershed size, precipitation patterns, and other factors. Example annual hydrographs of two rivers containing riverscour are presented in Figure 4. Flow rates can also change quickly during thunderstorms. Along the Obed and Big South Fork of the Cumberland River, Murdock et al. (2007) documented flows that increased from 100 to 6000 cfs in mere hours. Flood periodicity on the Blue River averages 2.6 floods annually, but

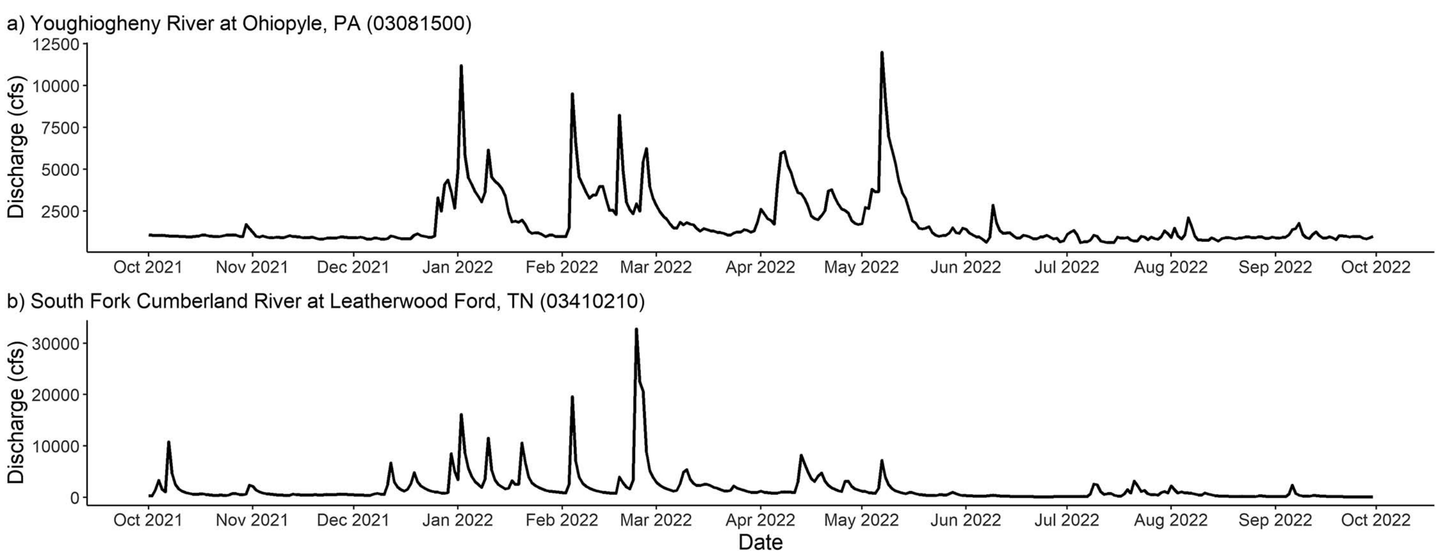

Figure 4.—Hydrograph comparison of the (a) Youghiogheny River and (b) Big South Fork of the Cumberland River. The Youghiogheny River is a regulated river whose hydrograph is characterized by attenuated peak flows and sharp falling limbs, whereas the unregulated Big South Fork of the Cumberland River has falling limbs that gradually return to baseflow conditions after a high flow event.

most floods last one day or less (Homoya and Abbrell 2005). For fluvial communities along the Potomac River, Lea (2000) reported mean flooding recurrence intervals, percent inundation percentages, and annual probability of flooding percentages, all based on a 68-year record. Across the spectrum of floodplain communities of the Potomac, most riverscour communities flood 0.8–7.5 times per year, have a percent inundation of 0.3–7%, with an annual probability of flooding of 15–99%. In our region's Central Appalachians and Mid-Atlantic sections, riverscour habitats are often subjected to winter ice scour (Cartwright and Wolfe 2016; Vanderhorst 2017).

High-intensity floods can denude vegetation from river bars and may restructure some bars by transporting alluvial boulders (those capable of being moved by river flows) and shifting cobble (Naiman et al. 1993; Bailey and Coe 2001; Vanderhorst et al. 2007; Wolfe et al. 2007). Williams (1983) stated that flows of 14,000–32,000 cfs are required to move boulders 1 m in diameter. By comparison, medium-intensity floods may uproot trees but shrubs and herbaceous vegetation usually remain intact (Wolfe et al. 2007). In more northern portions of the region, stream ice may shear trunks and branches of trees and shrubs.

While the presence of water and duration of flooding play major roles in sorting riverscour communities and species, another key factor is drought. The abundance of rock and porous sand, when coupled with their exposed, sunny position, makes them prone to drought stress. Open riverscour grasslands and shrublands have high insolation rates, some with at least 6–8 hr of direct sunlight. Daytime surface temperatures in open riverscour have not been measured to our knowledge, but given the high degree of solar insolation and surface bedrock exposure, it is conceivable that they experience temperatures similar to glades and barrens (Cartwright and Wolfe 2016).

Spring floods routinely knock back taller woody plants and periodically interrupt spring-blooming species, but the flowering and fruiting windows of most summer–fall plant species are less frequently interrupted by floods in riverscour systems with natural flood regimes. Summer–fall floods may be more common in some regions like the Appalachians. For Indiana's Blue River, Homoya and Abbrell (2005) present some of the few statistics regarding flow impacts on the federally endangered *Solidago shortii*, which experiences flood events an average of 2.6 times per year during winter and spring but not within the late summer–fall flowering period of this species (based on data from 1931 to 2003). Only nine of the 72 years they evaluated did not have flood events. For the federally threatened *Conradina verticillata*, Shea and Roulston (1996) report "that some populations may be flooded three to seven times a year for up to three days at a time," mostly in winter (Pennington 1992).

Cartwright and Wolfe (2016) reviewed the ecological adaptations of riverscour species, which include dispersal methods that allow floods to disperse seeds and vegetative propagules, tendency toward clonal reproduction, deep and strong anchor roots, shade intolerance, drought tolerance, inundation or high water table tolerance, tendency to senesce in fall, and persistence through seasons with highest flood potential as perennating rootstocks. They also considered the ability to recolonize rapidly following disturbance events as an attribute of riverscour species. While this certainly holds for those in some riverscour habitats, such as less stable sandy shorelines, it might not hold for more stable riverscour grasslands and shrublands. For these, many of the species are conservative and have poor dispersal capabilities.

Many species typical of mesic forests cannot withstand the combination of high flood intensity and associated abiotic stress regimes (e.g., high sunlight and drought); therefore, perennial grasses, forbs, and shrubs have a competitive advantage (Wolfe et al. 2007). The periodic scouring and inundation maintains riverscour communities in a state of disequilibrium, preventing them from reaching either climatic or edaphic climax states (Hupp 1983).

Vegetation Classification: The International Vegetation Classification (IVC) currently uses "riverscour" in its names at several levels in its hierarchical classification system, including for one Macrogroup, three Groups, eight Alliances, and 35 Associations (NatureServe 2022). Not all IVC vegetation types that might be considered riverscour have "riverscour" in their unit name. Thus, the IVC classification of riverscour in the EUNA is arranged in a complex hierarchy that is difficult to query or summarize. In addition, the development of Associations and Alliances has not been even across the EUNA. Riverscour in the northeastern part of the EUNA are relatively well classified in the IVC, facilitated by Natural Heritage Programs and NatureServe work, spurred by funding from the National Park Service (Vanderhorst et al. 2007, 2008, 2010; Teague et al. 2020). However, classification of riverscour Alliances and Associations needs more development throughout the region.

Flora: The flora of riverscour communities is very rich despite their small size and insular nature. While the known vascular flora across all EUNA riverscour systems has yet to be compiled, it likely exceeds 1500 species, with over 931 taxa documented in riverscour plots in West Virginia alone (WVDNR 2023). The number of species and infraspecific taxa in riverscour per river ranges from 85 to 464 taxa (Vanderhorst et al. 2007, 2008, 2010). Few floristic studies have been completed that cover the entire extent of riverscour communities along a given river. For an additional informative review of riverscour floristics, see Lea (2000), Anderson (2016), Rodgers (2016), Brock (2017), and Perles et al. (2023).

Known Occurrences

Geographic Distribution within EUNA: Cartwright and Wolfe (2016) provided a list of rivers with riverscour communities in the southeastern U.S. east of the Mississippi River and south of the Ohio-Potomac. A few streams with known riverscour to the north (e.g., Delaware River) and west (Pedernales River, Allegheny River) of our study area boundary are also mapped since they either flow into the study area or are tributaries to streams that enter the area.

To create a map of riverscour habitats across our EUNA study area, we assembled known riverscour community and plant element occurrences provided by Natural Heritage Program botanists and ecologists. Additional sources of data include vegetation plots, monitoring data, collections of riverscour associated plant species, and other expert knowledge from riverscour researchers. These were mapped into a GIS by intersecting each mapped scour element to the nearest medium resolution National Hydrography Dataset flowline (EPA 2012). Mapped riverscour reaches were reviewed by the authors and other regional experts. These flowlines represented the scour in subsequent analyses for geophysical factors and protected lands.

We mapped 1322 NHD flowline reaches containing riverscour habitat totaling 2385.8 km across our study area. A summary by state is presented in Table 1. Arkansas led the states with 644.6 km of riverscour across 54 unique streams, closely followed by West Virginia with 580.0 km across 30 unique streams. Missouri has the least amount of mapped riverscour with 3.3 km mapped across one river system, which we consider to be likely undermapped.

We identified 60.1 km (47 flowlines) across seven streams that have historical scour that has been destroyed by inundation by dams or for river navigation (Figure 2). Nearly half (29 km) of this lost riverscour habitat occurred along the Tennessee River, known as the Muscle Shoals, which was inundated and lost under Wilson Lake. However, due to the difficulty of locating historical riverscour on maps, we believe this total number is a significant underestimate.

Ecological Significance

The ecological significance of riverscour habitats is focused here on botanical composition. Their enhanced structural stability, high degree of insolation, and floristic contributions from adjacent upland, riparian, wetland, and aquatic ecosystems foster high species richness while enabling them to support long-lived, conservative perennial graminoids, forbs, pteridophytes, vines, and shrubs. Gnarled or prostrate, old-growth, flood-coppiced trees often exist. Some seemingly almost certainly contain old-growth specimens, although the only dendroecological study within EUNA, from West Virginia's New River, found most specimens to be less than 50 y old (DePinho and Saladyga, in review).

Rare Flora: Riverscour communities support a disproportionate number of rare species, given the small size of the ecosystem. While there are highly G-ranked (G1-G3) taxa, including several Federally listed, that are endemic or near endemic to riverscour habitats, these ecosystems also support outstanding numbers of locally rare (S1-S3), but globally secure (G4-G5), species. In many cases, these species use riverscour habitat at the periphery or geographically disjunct portions of their range, while they are typically found in other open ecosystems (e.g., pine savannas, prairies, glades, barrens, fens) at this core.

We analyzed a five-county area centered on the northern Cumberland Plateau of Tennessee covering 678,000 ha and found that riverscour makes up less than 1% of the area but contributes at least 37 (25%) of the region's 150 state- and federally-listed vascular plant species. This supports Wolfe et al.'s (2007) contention that alluvial bars are among the richest habitats for rare plants of this region. Fourteen of 36 (39%) rare plant taxa reported from the Gauley River National Recreation Area were found in riverscour habitats, which comprise a minute fraction of the total study area (Streets and Vanderhorst 2010; Vanderhorst et al. 2010).

A review of endemic and rare plant species of EUNA riverscour is being assembled by Knapp et al. (in prep). Examples of strict riverscour endemics include *Alnus maritima* ssp. *oklahomensis* (Schrader and Graves 2003), *Baptisia australis* sensu stricto, *Conradina verticillata*, *Eurybia saxicastellii* (Campbell and Medley 1989), *Marshallia pulchra* (Knapp et al. 2020), *Pityopsis ruthii*, *Solidago arenicola* (Keener and Kral 2003), *Solidago plumosa* (Small 1898), *Sporobolus arcuatus* (Rogers 1970), and *Vernonia lettermannii* (Gray 1880). Near-endemic taxa of riverscour, those with 90% of their known occurrences in riverscour habitats, include *Amsonia hubrichtii* (Woodson 1943), *Clematis cumberlandensis* and *C. ouachitensis* (Murphy et al. 2022), *Harperella nodosa*, *Spiraea virginiana*, and *Vitis rupestris*. Currently, multiple apparently undescribed endemic species known from riverscour communities of EUNA are under study and awaiting description. One globally extinct species, *Orbexilum stipulatum*, was endemic to EUNA riverscour (Knapp et al. 2021). It was first collected during the 1830s at Falls of the Ohio River, Kentucky, but has not been seen since last collected by C.W. Short in 1842 (Baskin et al. 2007).

Rare Fauna: Faunal studies have documented insects at select sites (Hudgins et al. 2012), but no other groups (birds, mammals, reptiles, amphibians, snails, etc.) have been surveyed systematically to our knowledge. Steury et al. (2009) investigated the bee fauna of a riverside grassland in the Potomac Gorge in Virginia and found 91 taxa within 28 genera. Several of these species are rarely documented in Virginia, and at least one species (*Megachile addenda* Cresson) is more commonly associated with sandy, xeric habitats in the Coastal Plain. Otherwise, very limited studies of pollinators have been done for specific rare plants, such as *Conradina verticillata* (Roulston 1994). Moore et al. (2021a) studied the impacts of lepidopteran use of *Baptisia australis* in Pennsylvania, documenting reductions in seed set of this rare species. The cobblestone tiger beetle (*Cicindela marginipennis* Dejean) is a specialist on major rivers where water currents are strong enough to periodically scour beaches and expose cobbles and larger stones along shorelines (NatureServe 2022). Populations of this species are currently extant along nine rivers, from Alabama to Maine. Flooded channels, depressions on riverscour, cobble beds dominated by *Justicia americana* L. cobble beds, and mats of riverweed (*Podostemum ceratophyllum*) provide habitat for aquatic invertebrates (e.g., mayflies, caddisflies), and high abundance of biomass of benthic macroinvertebrates (Hutchens et al. 2004; Cartwright and Wolfe 2016). Adjacent "Highland" riverine environments are recognized centers of aquatic biodiversity, rich in endemic fish, crayfish, and aquatic salamanders (Hoagstrom et al. 2014).

Biogeography

Cartwright (2019) categorizes riverscour as "insular" ecosystems with sharply defined boundaries separated from adjacent ecosystems by steep environmental and ecological gradients. These ecosystems are rich in species from nearby grasslands, woodlands, wetlands, and forests. A select few species may not occur anywhere in the surrounding region and are often disjunct from other ecoregions, sometimes by dozens to hundreds of kilometers. These ecosystems also support highly disjunct elements, including glacial relicts (Medley and Wofford 1980), coastal plain wetland/savanna species (Sorrie and Weakley 2001), southwestern arid-adapted taxa (Van Auken 2018), and Midwestern prairie species (Brock 2017; USNVC 2022).

The presence of disjunct taxa raises intriguing questions as to how species disperse among and within insular riverscour systems. The geological evolution of riverscour systems and the dispersion of riverscour biota undoubtedly has been very complex, involving combinations of short- to long-distance dispersal and vicariance over epochs of geologic time from ancient to recent. These changes, impossible to untangle with surety, have resulted in the diverse modern assemblages of riverscour communities of EUNA.

Threats to Riverscour Ecosystems

There are numerous threats to riverscour communities, from those that obliterate riverscour habitats across entire watersheds (e.g., dam building and reservoir creation) to those that impact individual scour bars (e.g., trampling or invasive species). Some threats are current and ongoing, but some may present problems in the future.

Dams/Hydrological Alteration: Before the era of dam building, limited areas of riverscour systems (e.g., Falls of the Ohio River) were damaged or destroyed by dynamite or canals and locks to improve navigation during the 19th and early 20th centuries (Oakes 1917). Later, during the era of dam construction (ca. 1920s–1970s)—for flood control, hydroelectricity, and recreation—dams and their reservoirs destroyed an unknown amount of riverscour habitat before it could be mapped and inventoried. Patrick and Wofford (1981) reported that scour communities along the lower Big South Fork of the Cumberland River were destroyed due to construction of Wolf Creek Dam, forming the 26,521 ha Lake Cumberland. This essentially eliminated limestone riverscour habitats on the lower Big South Fork, whereas sandstone riverscour still exists in the upper unimpounded portions of the river. Label data from herbarium specimens of several riverscour-dependent plant species collected by E.J. Palmer and others along the Ouachita River in western Arkansas prior to the construction of Lakes Catherine, Hamilton, and Ouachita indicate extensive loss of riverscour habitat under these reservoirs (SERNEC 2022). Unfortunately, we now can only guess whether many impounded streams would have historically supported riverscour habitats, making it impossible to accurately estimate the amount of loss sustained by riverscour ecosystems of EUNA.

Dams destroy riverscour habitat upstream by inundation, and they degrade downstream river conditions by altering seasonality and intensity of flooding and blocking the downstream transport of seeds and clonal fragments (Ogle 1992). Most rivers with riverscour habitat in West Virginia have been dammed, leaving only the Greenbrier and Shavers Fork Rivers free-flowing for their entire lengths. Populations of riverscour species (e.g., *Baptisia australis*, *Spiraea virginiana*, *Vitis rupestris*), known from the Lower Allegheny, Monongahela, and Ohio Rivers, which have had their hydrology drastically altered by locks and dams, have been long extirpated (PNHP 2022; WVDNR 2022). On North Carolina's Yadkin River, two impoundments eliminated most riverscour habitat. Presently, only a 2 km stretch of natural, free-flowing river exists, providing habitat for the only population on earth of the G1-ranked *Solidago plumosa*—thought to be extinct until rediscovered in 1994.

The impacts to riverscour habitats downstream from dams due to hydrologic alteration present threats lasting decades after dams are constructed. In addition to eliminating natural flood cycles and flow intensities (Magilligan and Nislow 2005), dams limit rocks, woody debris, and/or ice from traveling downstream—key factors that keep riverscour ecosystems open through physical disturbance. Interruption of the scouring processes associated with flooding and winter ice promotes succession toward larger woody species and away from open, rare herbaceous riverscour communities (Westervelt et al. 2006). The Hiwassee River in Tennessee has a several-kilometer reach below the Appalachia Dam known as the "Dries Section." This reach is well known to kayakers because the reduction of natural flows has led to the channel becoming so overgrown with trees that they form a kayaking hazard. Farther downstream, these diminished flows also impact populations of the federally endangered, riverscour endemic, *Pityopsis ruthii* (Major et al. 1999), which needs open habitat free from woody plant competition. Increasing dominance by trees due to dam-caused disruption of natural floods threatens the globally rare Eastern Redcedar–Virginia Pine Flatrock Woodland community of the New River Gorge National River (Mitchem 2004; Vanderhorst et al. 2007).

Unseasonably high flows from controlled dam releases also threaten downstream riverscour ecosystems. The Youghiogheny Dam at Confluence, Pennsylvania, is congressionally authorized for management to include "whitewater recreation" where minimum flows of ~900 cfs are maintained from Friday through Sunday throughout the summer recreation season (USGS 2022). These recreational flows can be seen as small peaks during the summer months in the Youghiogheny River hydrograph in Figure 4. The Ocoee River of Tennessee has four dams and associated impoundments over 28 river-km, with much of the river highly controlled for summer whitewater recreation. For these and other rivers with altered flow regimes, the consistent slight elevation of the water table may affect the survivorship of riverscour-adapted plant species, especially xerophytic plants that are adapted to lower baseflows during summer–fall. Alternatively, it may reduce drought stress for flood-adapted shrubs in drought-prone elevated portions of riverscour bars (Wolfe et al. 2007), possibly giving such shrubs a competitive advantage over drought-adapted perennial grasses and forbs that comprise rare riverscour grassland communities.

Invasive Species: Riparian systems, including riverscour habitats, may be subject to increased invasion by exotic plant species compared to intact adjacent upland forests due to frequent disturbance, high propagule pressure, and nutrient-rich sediments (Planty-Tabacchi et al. 1996; Hood and Naiman 2000; Brown 2002; Naiman et al. 2005; Perles et al. 2023). Given the heterogeneity of riverscour habitats and their wide distribution, "the patterns of invasion and the particular species responsible appear to vary based on geographic region and riverscour community type" (Cartwright and Wolfe 2016). Invasive plants in riverscour may trap sediments, alter successional dynamics (Vanderhorst et al. 2007), and limit populations of rare endemics such as *Spiraea virginiana* (Ogle 1991). On the Caney Fork River of central Tennessee, *Deutzia crenata* is extremely abundant, perhaps more so than at any other known location in eastern North America (Brock 2017). Numerous studies have documented significant invasion of aquatic plant species in shallow riverine communities adjacent to riverscour habitats, including *Alternanthera philoxeroides*, *Egeria densa*, *Hydrilla verticillata* (monoecious biotype), *Murdannia keisak*, and *Potamogeton crispus* (Estes et al. 2010; Anderson 2016; Rodgers 2016). It is unclear if these aquatic invaders directly threaten adjacent terrestrial riverscour habitats.

Landscape Changes: Land use change throughout a watershed can also impact river hydrology. Urbanization leads to an increase in impervious surfaces and increases runoff to streams. This increased runoff, combined with increased wastewater releases from development, may affect future stream flows and could threaten the ecological integrity of riverscour habitats (Murdock et al. 2007; Wolfe et al. 2007; Cartwright and Wolfe 2016).

Pollution and Sedimentation: Pollution events have been documented along various streams with riverscour. In Tennessee, a tanker truck accident at a bridge resulted in an oil spill into Clear Creek (Obed Wild and Scenic River). No adverse implications have been documented, and this river continues to support high-quality in-stream riverine habitat for aquatic species, including the rare *Potamogeton tennesseensis*. On Alabama's Mulberry Fork of the Black Warrior River, coal mining and the release of wastewater have resulted in multiple fish kills, including one in 2019 where 220,000 gallons of anaerobic wastewater was released from a chicken farm that killed wildlife, including over 200,000 fish, rendering the river unusable for over 80 km downstream (Reich 2021). Shea and Roulston (1996) reported that coal fragments from nearby strip mines were deposited by spring flood waters in 1993 on a cobble bar along the Big South Fork, forming a layer 15 cm deep. The next flood removed these deposits. Fortunately, toxins in these river systems may "flush out" relatively quickly. Still, in cases where persistent pollution threats exist, or the pollutants are particularly toxic (e.g., acidic mine runoff; Shea and Roulston 1996; Murdock et al. 2007), even with short-term exposure, there could be impacts to riparian vegetation. In the last century, acid mine drainage from coal mining seriously degraded water quality, benthic macroinvertebrates, and fish populations in the Monongahela River Basin (Sams and Beers 2000), including riverscour reaches of the Buckhannon, Cheat, and Tygart Valley Rivers in West Virginia, but has not had obvious effects on riverscour vegetation, as evidenced by surveys (WVDNR 2022).

Urban runoff contains excess levels of nutrients, pesticides, herbicides, metals, and organic solvents (Hampson et al. 2000), which could pose a threat to riverscour habitats, but the "seriousness of this threat remains largely unexamined" (Wolfe et al. 2007). Similarly, Wolfe et al. (2007) noted that on the Emory River of Tennessee, there have been documented increases in stream flow corresponding to wastewater releases. However, they note that it is uncertain how much these releases affect riverscour vegetation both in terms of increased flow and nutrient dynamics.

Sedimentation due to road and trail construction, culverts, extensive logging in upland landscapes, and development have been identified as potential threats to riverscour due to increased sediment loads from topsoil erosion, which could alter flow regimes, sediment transport, and deposition dynamics (Taylor 2003; Murdock et al. 2007; Wohl 2014; Cartwright and Wolfe 2016). The extensive gravel bars found along streams in the Ozark Plateau are considered more extensive than in historical times due to extensive logging and land-clearing and subsequent erosion in regional uplands (Jacobson 1995).

Trampling: Streams with riverscour habitat tend to attract a higher volume of people because of their whitewater recreation, fishing, camping, and scenic opportunities. Yet more people brings greater potential for trampling sensitive natural communities and species. Open riverscour habitats are frequently used as portages or places for breaks during guided rafting trips or by kayakers, resulting in over-use and trampling (Cartwright and Wolfe 2016; PNHP 2022; WVDNR 2022).

Isolated, small-patch sand barren communities at the Obed Wild and Scenic River are favorite spots for campers and fishermen, and they suffer disproportionately from human impacts relative to other riverscour communities, as people choose these tiny (<0.01 ha) sand barrens for back-country campsites (Estes and Fleming 2008). These communities harbor significant concentrations of rare species and represent a unique, undescribed vegetation association. These sand barrens likely represent a critically imperiled community, so the fact that they are especially prone to human impacts is concerning.

In the middle of Tennessee's Ocoee River, a large outcrop harbors the federally endangered *Pityopsis ruthii*. The outcrop has metal plates anchored to the rocks advising rafters to "keep off" to avoid trampling the fragile population. Publicly accessible bedrock outcrops are frequently used as "beaches" for sunbathing and swimming, resulting in impacts such as trampled vegetation, human–wildlife conflicts, and litter (C. Tracey, pers. obs.). A large and important area of rare igneous riverscour on the East Fork of the Black River at Missouri's Johnson's Shut-ins State Park is one of the region's most heavily used stream access points for public recreation, drawing nearly 250,000 visitors in 2021 (MoDNR 2022). Shea and Roulston (1996) noted that trampling by people, horses, and vehicles presented "very critical threats" to some of the larger colonies of *Conradina verticillata*.

Climate Change: The threats outlined above often interact with each other, and when combined with climate change, they present a complicated array of factors that can have far-reaching effects on catchment-scale hydrological processes, ecological integrity, and biodiversity (Palmer et al. 2009; Weiskopf et al. 2020). Climate change impacts include changes in the frequency and magnitude of floods, low flows, the riparian soil/groundwater regime (Palmer et al. 2009), and landscape use changes due to influxes of environmental refugees (Shaw et al. 2020).

Recent climate observations and future models suggest that broad parts of the temperate EUNA region are expected to experience more frequent and intense summer rainfall, and less winter precipitation falling as snow (USGCRP 2018; Kutta and Hubbart 2019; Xu et al. 2020). In light of these projected regional differences in climate, we summarize potential

Table 2.—Notable riverscour protected by federal and state agencies. Manager codes as follows: NPS = National Park Service, USFS = US Forest Service, ACOE = Army Corps of Engineers.

Primary manager	Management unit	Rivers	States
NPS	Big South Fork National River and Recreation Area	Big South Fork of Cumberland River, New River [of Tennessee], Clear Fork	KY, TN
USFS	Cherokee National Forest	Hiwassee River, Nolichucky River, Ocoee River	TN
Arkansas Natural Heritage Commission/ Arkansas State Parks	Cossatot River State Park Natural Area	Cossatot River	AR
USFS	Daniel Boone National Forest	Buck Creek, Cumberland River, Laurel River, Little South Fork (of the Cumberland River), Marsh Creek, Rockcastle River	KY
NPS	Delaware Water Gap National Recreation Area	Delaware River	NJ/PA
ACOE	DeQueen Recreation Area	Rolling Fork (of the Little River)	AR
NPS	Gauley River National Recreation Area	Gauley River, Meadow River	WV
NPS	Great Falls National Park	Potomac River	MD, VA
NPS	Harpers Ferry National Historical Park	Shenandoah River	WV
Missouri Dept. of Natural Resources	Johnson's Shut-Ins State Park	East Fork Black River	MO
NPS	Little River Canyon National Preserve	Little River	AL
USFS	Monongahela National Forest	Shavers Fork (of the Cheat River)	WV
NPS	New River Gorge National Park and Preserve	New River	WV
NPS	Obed Wild and Scenic River	Emory River, Obed River, Daddys Creek, Clear Creek	TN
Pennsylvania Department of Conservation and Natural Resources	Ohiopyle State Park	Youghiogheny River	PA
USFS	Ouachita National Forest	Alum Fork (of the Saline River), Irons Fork (of the Ouachita River), Fourche LaFave, South Fourche LaFave, Ouachita River	AR
USFS	Ozark National Forest	Big Piney Creek, Frog Bayou, Mulberry River	AR
Texas Parks and Wildlife	Pedernales Falls State Park	Pedernales River	TX
West Virginia Division of Natural Resources	Snake Hill Wildlife Management Area, Cheat Canyon Wildlife Management Area	Cheat River	WV

climate-related impacts that may affect riverscour differentially across the study area.

The most likely potential impact to riverscour habitats due to climate change is the alteration of flow regimes due to changes in local or regional precipitation patterns. The effects of altered precipitation patterns may also extend flows and flooding into the summer months. For example, more frequent summer storm events have resulted in high-flow events when many rivers historically tend to have their lowest seasonal flows. We may already be seeing a shift toward more severe summer flood events, which is expected under climate change scenarios for large parts of EUNA (Kirchmeier-Young and Zhang 2020). Recent (May 2010, August 2021, July 2022) floods that devastated parts of central Tennessee and eastern Kentucky were all considered 1000-year flood events (Crawford et al. 2023). These unseasonably high flows may impact growing season riverscour vegetation through physical damage, reduced reproductive output, or other impacts. Future climate change scenarios involving fluctuations in the timing of flood events or decreases in flooding thus could potentially impact riverscour systems. Climate change may also greatly influence the composition of the plant communities of ice-scour communities (Thellman et al. 2021). Without the freeze–thaw and naturally occurring ice-scour, woody encroachment could make the riverside less habitable for rare conservative heliophyte species.

Riverscour Conservation

Terrestrial protected areas rarely ensure adequate protection of rivers and the biodiversity found within them (Herbert et al. 2010). Although mainly depending on the ecological properties of the surrounding terrestrial environment, rivers are ecological systems by themselves, characterized by their linearity. They are organized in connected networks, complex and ever-changing. The legacy of dam building in the 20th century, coupled with pollution, sedimentation, and decreases in water availability due to drinking water withdrawal, has altered many rivers and compounded the challenges of riverscour conservation now and in the future.

Many riverscour ecosystems are found within protected areas within the study region (Table 1). This is partially due to overlap in areas that historically have been protected, such as areas of high topographic diversity, and recreation features such as whitewater, deep gorges, cliffs, etc. However, few, if any, examples of riverscour exist within a completely protected watershed.

Following the mapping of stream reaches containing riverscour ecosystems in GIS, described above, we determined the percent of streams with riverscour that flow through protected lands.

According to our analysis, 1754.5 km (71%) of stream reaches mapped as containing riverscour habitat within the study area overlap or are adjacent to protected land (Table 2). Of this total, 37% is land strictly designated for biodiversity protection

(GAP1/2), and the remaining 63% is managed for multiple uses (GAP3/4 status). The US Forest Service (USFS) manages the most riverscour habitat of any federal agency, with ~508.5 km of riverscour containing stream reaches, followed by NPS with 327.9 km. Depending on the status or local laws, the river channel may or may not be included within parcel boundaries; as in some jurisdictions (e.g., Pennsylvania, West Virginia) the state has ownership of the streambed. For example, the documented occurrences of riverscour communities of the Middle and Lower Youghiogheny River are nearly completely protected by a combination of state ownership and private conservation organizations. We should note that due to the combination of mapping accuracy, local policy on stream and river ownership, and other geographic representation factors, these protection estimates carry a small amount of nonquantifiable uncertainty.

Sixty percent of riverscour across the USFS land within EUNA is found in Arkansas within the Ouachita and Ozark National Forests. Other USFS holdings with notable concentrations of riverscour include the Daniel Boone National Forest (KY), the Cherokee National Forest (TN), and the Monongahela National Forest (WV). The National Park Service (NPS) manages several important riverscour habitats across its units, including the Big South Fork National River and Recreation Area (KY, TN), Bluestone National Scenic River (WV), Chesapeake & Ohio National Historical Park (MD, WV), Delaware Water Gap National Recreation Area (NJ, PA), Gauley National Recreation Area (WV), George Washington Memorial Parkway (DC, MD, VA), Great Falls Park (VA), Harpers Ferry National Historical Park (WV), Little River Canyon National Preserve (AL), New River National Park and Preserve (WV), Obed Wild and Scenic River (TN), and Ozark National Scenic Riverways (MO). Other key land managers of riverscour habitat include the Army Corps of Engineers, Tennessee Valley Authority, and various state conservation agencies.

The National Wild and Scenic Rivers System (NWSRS) was created by Congress in 1968 (Public Law 90-542; 16 U.S.C. 1271 et seq.) to preserve certain rivers with outstanding natural, cultural, and recreational values in a free-flowing condition for the enjoyment of present and future generations. The Act is notable for safeguarding the processes of scour and flooding. The Act purposefully strives to balance dam and other construction at appropriate sections of rivers with permanent protection. To accomplish this, it prohibits federal support for actions such as constructing dams or other in-stream activities that would harm the river's free-flowing condition, water quality, or outstanding resource values. The following rivers known to harbor riverscour ecosystems have been designated NWSRS: Arkansas, Big Piney Creek and Cossatot River; Tennessee, Obed River (and its tributaries Clear Creek, Daddy's Creek, and a portion of the Emory River).

In addition to the NWSRS, some states have similar state-level acts. Within our 24-state study area, 12 states (AR, KY, LA, MS, NY, NC, OH, OK, PA, SC, TN, and VA) have a wild and scenic rivers program. In Tennessee, large sections of the Duck and Hiwassee Rivers are designated State Scenic Rivers (SSRs). The Kentucky Wild Rivers Program, established by the Kentucky Wild Rivers Act of 1972 and administered by the Office of Kentucky Nature Preserves, designates a linear corridor encompassing all visible land on each side of the river up to a distance of 610 m (2000 feet). Within this viewshed, the Wild Rivers program strictly prohibits activities such as surface mining, timber clearcutting, and dam construction, or other in-stream disturbances. While the Kentucky Act allows existing residential and agricultural uses to continue, other development activities that might impair water quality or natural conditions are regulated. While the protection opportunities afforded by these acts vary, they do provide another tool for protecting riverscour habitats.

Future Research

Our review has illuminated knowledge gaps or areas of research, along with those identified by Cartwright and Wolfe (2016), that are still needed to understand these understudied ecosystems more fully.

Inventory and Monitoring: While some river systems have been thoroughly inventoried botanically, we estimate that more than 90% of the rivers with documented riverscour have not, and studies of other organismal groups (vertebrates, insects, lichens) have barely scratched the surface. With the high rate of endemism and presence of undescribed species endemic to specific river reaches, more studies of understudied riverscour systems would be expected to reveal new rare species populations and additional undescribed species. Cartwright and Wolfe (2016) noted that understanding of the use of riverscour habitats by animals is lacking. It is clear that more research is needed for all taxa in order to elucidate broader community dynamics, such as trophic interactions. Estes et al. (2010) called for developing an early-detection and rapid-response monitoring system to help identify invasive species that could wreak havoc in riverscour and associated riverine ecosystems. While some long-term monitoring has been done on invasive species (Perles et al. 2022) and federally threatened plants at specific sites, monitoring efforts are needed for others to identify potential trends in populations that may need adaptive management. Perles et al. (2022) provided recommendations for monitoring riverscour communities to help understand the impacts from threats such as invasive species, hydrologic alterations, climate change, and other factors over time.

Taxonomic Research, Population Genetics, Phylogeography: The high degree of plant disjunction associated with riverscour ecosystems and resulting genetic isolation raises intriguing questions about riverscour biodiversity and the need for further research. Anders and Murrell (2001) found that populations of *Spiraea virginiana* in different river drainages in close proximity were genetically and morphologically similar, compared to those in more disjunct drainages, and possibly displayed a complex history of migration in response to Pleistocene climate change. While they stopped short of differentiating these different populations as distinct species, it would be interesting to see what newer molecular approaches might reveal about them. Recent studies of the barcheek darter complex (*Etheostoma basillare* Page, Hardeman & Near, *E. derivativum* Page, Hardman & Near, *E. obeyense* Kirsch, *E. smithi* Page & Braasch) in multiple tributaries of the Caney Fork River system in Tennessee found that the different rivers supported genetically distinct but morphologically indistinguishable lineages (microendemics) that have diverged by an estimated 0.6–8 million years (Hollingsworth and Near 2009). Following this example, could some disjunct populations of riverscour endemics isolated in different watersheds also represent newly speciated micro-endemics? What about populations of long-range disjuncts such as *Sporobolus arcuatus*, with populations east and west of the Mississippi River separated by hundreds of kilometers? Combining classic morphological studies, modern molecular phylogenetics, population-level analyses, and phylogeographic investigations involving divergence time estimates could reveal cryptic species or important patterns of genetic diversity confined to separate stream systems.

Autecological Studies of Riverscour Species and Tolerance Thresholds for Change: More research is needed to investigate how riverscour species are affected by ecological changes, such as alterations in streamflow, changes in nutrients or pollutants, shading, invasive species competition, and siltation. In particular, how do such changes affect reproduction, growth, and dispersal by fragmentation or seeds, plant–pollinator interactions, and long-term population trends? Limited studies have been done to date, mostly on federally listed taxa, including *Conradina verticillata* (Albrecht and Penagos 2012), *Harperella nodosa* (Buthod and Hoagland 2013), *Pityopsis ruthii* (Thomson and Schwartz 2006; Moore et al. 2021b), and *Spiraea virginiana* (Ogle 1991; Brzyski and Culley 2013; Rossell et al. 2013). Emerging data from dendroecology could be insightful for understanding ecological change in riverscour ecosystems in recent times (McCord 1990; Ballesteros-Canovas et al. 2015; DePinho and Saladyga, in review).

Climate Change Impacts to Riverscour: Climate change will profoundly impact all ecosystems, and riverscour ecosystems may be particularly vulnerable due to the role of flood water and, in the northern portion of EUNA, winter ice in maintaining the open canopy of riverscour grassland and woodland communities. Building on Cartwright and Wolfe (2016), we identified three major categories of climate change vulnerability of riverscour species.

The first includes changes to scour processes, where flow-regime changes resulting from shifts in regional precipitation patterns would likely influence streamflow, especially flood magnitude, frequency, and seasonality. For example, increases in summer high-flow events may profoundly affect the flowering, dispersal, and germination of scour-adapted plant species. We recommend using coupled ecological and hydrological modeling to understand how changes in flood events (Noss et al. 2021) may result in changes to riverscour habitats. Secondly, individual species may be vulnerable to climate change. Climate change vulnerability assessments in West Virginia (Byers and Norris 2011) using NatureServe's Climate Change Vulnerability Index (CCVI) tool (NatureServe 2016) rated two riverscour species as highly vulnerable and two additional species as moderately vulnerable. Additional vulnerability assessments in Pennsylvania exhibited similar results (S. Schuette, pers. comm.). It is important to note that these assessments were made at the individual species level and are not indicative of the response within an ecological community. The third category may be how invasive species affect riverscour habitats under different models of climate. Hellmann et al. (2008) postulated that exotic species invasions could be substantially influenced by regional changes in temperature and precipitation patterns, and thus this could facilitate or exacerbate the expansion of exotic species into riverscour habitats.

Restoration of Riverscour Below Dams: More study is needed to understand the impact of controlled releases of water from dams on downstream river systems (Magilligan and Nislow 2005) and riverscour habitats. Additionally, some rivers are now facing decades of scour suppression and have seen the transformation of riverscour systems into more woody-dominated riparian communities. Such riparian transformations threatened globally imperiled species such as *Pityopsis ruthii* and *Solidago plumosa* that require high-quality open riverscour habitat.

Research and experimentation are being conducted along several rivers through projects such as the Sustainable Rivers Program (https://www.nature.org/en-us/what-we-do/our-priorities/protect-water-and-land/land-and-water-stories/sustainable-rivers-project/), a partnership between the US Army Corps of Engineers and The Nature Conservancy, which aims to provide adaptive management of dams to provide ecologically relevant flows (Warner et al. 2014). Further research, especially in timing, duration, and severity of scouring flows, is needed to understand how to reverse decades of scour alteration to heal riverscour communities.

CONCLUSIONS

In this work, we have attempted to summarize what is known about the natural history of an entire ecosystem across its geographic range. Riverscour habitats are often overlooked riparian grasslands, shrublands, open woodlands, and rock outcrops maintained by flooding and/or ice combined with harsh edaphic conditions. They are unusual islands of open habitat within the primarily wooded, topographically dissected landscapes of eastern North America.

While the biodiversity conservation value of riverscour has been well established, these ecosystems have never been clearly defined—at least in the published literature. Thus, this paper attempts to define the term "riverscour" to lay the foundation for subsequent investigations into their ecology, physical processes, species composition, restoration, and management. Riverscour has been variously recognized in ecological classification efforts, ranging from being lumped into broader floodplain types to being identified as unique associations. This has made it difficult to consistently represent these ecosystems in regional and national classification efforts such as the U.S. National Vegetation Classification. We hope that this paper leads to further efforts to inventory and describe these habitats, elevate their profile, and integrate them into classification and subsequent mapping efforts.

In this age of significant anthropogenic alteration and degradation of the region's ecosystems, especially grasslands and other open communities, it is imperative that we gather and synthesize information about riverscour while these ecosystems remain relatively intact. Many rare and endemic species occur in riverscour, including several apparently undescribed species in urgent need of study and description. High species richness and diversity, coupled with historical losses and degradation of many riverscour systems by dam construction, hydrologic alterations, invasive species, recreation pressure, and other factors, make protection and proper management of riverscour ecosystems especially important in conserving the native biodiversity of eastern North America.

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