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Source: Natural Areas Journal, 44(4) : 223-239

Published By: Natural Areas Association

URL: https://doi.org/10.3375/2162-4399-44.4.233

Research Article

Tree Rings and Aerial Imagery Illustrate a Multi-Century Trend from Open Lands to Closed Forest at Eagle Valley, Southwest Wisconsin, USA

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Associate Editor: John N. Williams

ABSTRACT

An environmental history of Eagle Valley Nature Preserve, situated among the bluffs of the Mississippi River in southwest Wisconsin, USA, describes a dynamic landscape with multi-century ecological trajectories shaped by the interacting effects of climate and human engagement with the land. Crossdated tree-ring establishment dates of cut stumps of eastern redcedar (*Juniperus virginiana*) trees hint at possible afforestation in the 1300s and 1400s CE following reorganization of the Mississippian mound-building culture. Historical observations from the seventeenth century describe an open landscape with only scattered trees restricted to ravines and other areas protected from passing prairie fires. Outer ring dates on redcedar stumps indicate early 1800s harvest dates and illustrate impacts of European landuse that occurred decades before the General Land Office Survey at this location. Oak (*Quercus macrocarpa* and *Q. alba*) and eastern redcedar establishment dates in the mid-1800s suggest a change in disturbance regime related to shifting landuse initiated by European colonization, while twentieth century aerial imagery illustrate a continued trajectory toward closed-canopy forest and simplified landscape patterns. Increasing moisture availability over recent decades and the cessation of grazing likely amplified these changes. Based on tree-ring data and field observations, it appears likely that the forests covering much of Eagle Valley today represent the first closed-canopy system to occur at the site in at least a millennium. Current land stewardship activities to maintain and expand prairie and savanna communities are working against a multi-century trend toward increasing forest cover and landscape closure at a regional scale.

Index terms: aerial imagery; dendrochronology; Driftless Area; environmental history; landscape change; Mississippi River; Wisconsin

INTRODUCTION

Land stewardship is a dynamic process that, when done well, recognizes the implications and influences of history on current conditions and uses this understanding to cultivate diversity and resilience in an ever-changing and uncertain future (Higgs et al. 2014). Identifying realistic management goals and the objectives required to achieve them depends on understanding the long-term dynamics of the system being managed, including the recognition of local trajectories operating within the context of broader regional and global trends. The current and recent structure and composition of plant communities can provide some insight into the drivers and likely outcomes of ecological change, but the relatively brief records we have of most ecosystem conditions result in substantial uncertainty around longer-term dynamics. A historical perspective can improve understanding of how ecological systems respond to changes in disturbance regimes, climate, and human landuse over centuries to millennia (Barak et al. 2016). Historical ecology, informed by paleoecological data, provides a powerful framework to bracket uncertainty and constrain perspectives of potential environmental conditions in both the past and future (Swetnam et al. 1999).

In the Driftless Region of southwest Wisconsin, dramatic changes in landcover have occurred since the time of European settlement. The prairies and oak savannas that covered much of the region have largely been converted to agricultural fields and pastures (Nuzzo 1986), while selective logging and fire suppression have caused an overall homogenization of forest communities, with pre-settlement oaks (*Quercus* spp.) and other fire-adapted species lingering in the canopy of stands that are now dominated by fire-intolerant hardwood species (Rhemtulla et al. 2009). Encroachment of urban development, invasive species, conversion to agriculture, and fragmentation of prairies and savannas have led to substantial impacts on species diversity (Rogers et al. 2009), with associated impacts on native wildlife populations (Peterjohn and Sauer 1999). The role of climate change in driving ecological change is less certain, but trends of increasing mean seasonal temperature and precipitation are evident for the region (WICCI 2011) and likely translate to shifting competitive interactions (Gilman et al. 2010). The collective impacts of these changes are substantial, yet a growing number of landowners and managers are working to restore prairie and oak savanna habitat to bolster landscape diversity. Eagle Valley Nature Preserve, located along the Mississippi River in the Driftless Region of southwest Wisconsin, provides a unique opportunity to build a more complete understanding of how stewardship efforts are operating within historical legacies of human engagement and environmental change that began centuries ago.

Here, we weave together insights from multiple lines of evidence including tree-rings, aerial imagery, survey records, and other historical documents to establish a multi-century record of vegetation change at Eagle Valley. This was accomplished through the following research objectives:

1) develop annually precise, multi-century tree-ring records from eastern redcedar (*Juniperus virginiana*) and oak (*Quercus alba* and *Q. macrocarpa*) trees growing among the bluff prairies and adjacent slopes of Eagle Valley to document the timing of tree establishment and patterns in growth that represent landscape change over recent centuries;
2) identify and utilize the long-term relationships among climate and tree growth at Eagle Valley to provide historical context for current climate conditions and to determine if temperature and moisture conditions for Eagle Valley are within the historical range of variability for the site; and
3) examine landcover change from historical aerial imagery and historical documents to determine historical and current trends in landscape patterns and their links to climate, landuse, and vegetation change over recent centuries.

The long-term environmental history established through this research provides important historical context for the current ecological conditions at Eagle Valley and identifies multiple key considerations for planning future stewardship of the property.

METHODS

Study Area

Eagle Valley Nature Preserve (EVNP) is a private 590 ha preserve owned since 1989 by Kohler Co. and the Kohler Trust for Preservation (Figure 1A). EVNP is situated within the heart of the Driftless Region, a loosely defined area that has largely been spared the depositional and scouring effects of one or more of the Pleistocene glaciations (Chamberlin and Salisbury 1886), and on the western edge of the more formally defined Driftless Area, which was unglaciated throughout the entire Pleistocene (Carson et al. 2023). Spanning 4.3 km of frontage along the Mississippi River in Glen Haven township, Grant County, Wisconsin (Figure 1B), the topography of the preserve is diverse and dramatic, with high-relief incised valleys, and frequent bedrock outcrops and bluffs that jut up to 115 m above the river floodplain. The bedrock underlaying the site consists of a sequence of relatively flat-lying Paleozoic sedimentary units of Ordovician age (Steinhilber et al. 1961; Mudrey et al. 1982; Stewart et al. 2022), the uppermost unit of which is the Galena Formation (Supplemental Figures S1 and S2). The Galena Formation is the principal ore-bearing rock unit throughout the Upper Mississippi Valley Zinc-Lead District (Heyl et al. 1956), and historical records from the region indicate the presence of several former lead digs and mine shafts within EVNP (Pepp et al. 2019), with on-site evidence of past mining activity described later in this paper.

The diverse topography of EVNP supports a variety of habitats, including native goat (bluff) prairies, upland prairie, dry-mesic, mesic, and lowland forests, oak savanna remnants, and 75 ha of prairie conservation plantings on former agricultural fields that were established primarily in the mid-1990s when restoration activities within the preserve began in earnest. Forest cover is composed primarily of hardwood trees common to southern Wisconsin forests (Curtis and McIntosh 1951; Curtis 1959), with upland trees including bur oak (*Quercus macrocarpa*), white oak (*Q. alba*), red oak (*Q. rubra*), shagbark hickory (*Carya ovata*), black cherry (*Prunus serotina*), white ash (*Fraxinus americana*), American elm (*Ulmus americana*), red elm (*Ulmus rubra*), ironwood (*Ostrya virginiana*), hackberry (*Celtis occidentalis*), sugar maple (*Acer saccharum*), basswood (*Tilia americana*), and black walnut (*Juglans nigra*), with occasional inclusion of more southern species such as honey locust (*Gleditsia triacanthos*) and chinkapin oak (*Q. muehlenbergii*). Eastern redcedar trees occur primarily along the edges of old fields and among rock outcrops. Silver maple (*A. saccharinum*), red maple (*A. rubrum*), and eastern cottonwood (*Populus deltoides*) are common in the floodplain. The prairie and forest floor vegetation communities are highly diverse and broadly representative of dry to mesic tallgrass prairie, savanna, and northern forest communities (Curtis 1959; Cochrane and Iltis 2000).

Climate in the region is humid continental (Dfa) with four distinct seasons, large seasonal temperature differences, warm to hot and often humid summers, and cold winters (Beck et al. 2018). A weather station at Guttenberg, Iowa, across the Mississippi River valley and directly adjacent to Eagle Valley, provides a continuous record of temperature and precipitation from 1949 to 2023 (National Weather Service 2023). The annual mean temperature at this weather station is 9.3°C with monthly mean maximum and minimum temperatures of 23.6°C in July and −7.3°C in January (Supplemental Figure S3). The average summer temperature (June, July, and August) is 22.4°C, and the average winter temperature (December, January, and February) is −5.4°C. Precipitation peaks in June and July when the summer maximum is enhanced by convection storms as temperature increases toward mid-summer. Mean annual total precipitation is 83.6 cm, of which 28% occurs in June and July. January and February are generally the driest months of the year.

Cultural History of Eagle Valley

The long-term engagement of people with this landscape is exemplified by the presence of at least 70 conical, linear, and effigy mounds that exist at locations overlooking the Mississippi and Eagle Valley (Figure 1C), the presence of which links this place to Mississippian mound-building cultures and the emergence of Oneota cultures in the eleventh and twelfth centuries (Theler and Boszhardt 2000). Archaeological surveys contracted by EVNP suggest that these mounds were constructed between 650 and 1150 CE, with a few early mounds dating back to 800 BCE (Birmingham and Rosebrough 2017). Cultural development and engagement with the landscape at Eagle Valley since the mound-building era is complex and rich. Middle (Developmental, 1300–1600 CE) Oneota communities began using ridged-field agriculture (Gallagher et al. 1985) to grow the three sisters (corn, beans, and squash), oftentimes in broader valleys, and longhouses became the preferred form of living quarters

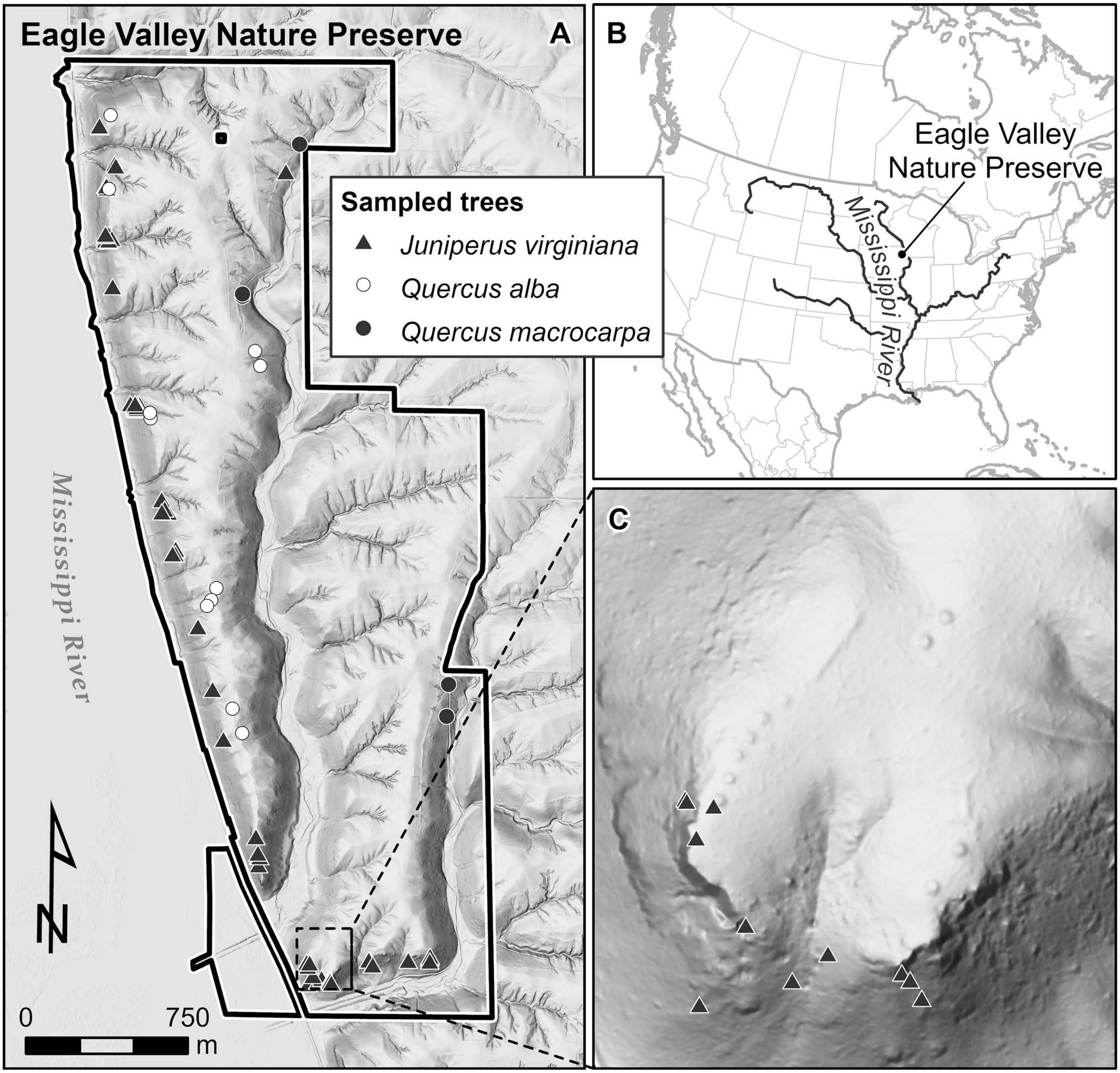

Figure 1.—Study area map showing (A) the extent of Eagle Valley Nature Preserve (EVNP) along the bluffs of the Mississippi, with locations of sampled eastern redcedar and oak trees, (B) the position of EVNP in the Upper Mississippi Drainage, and (C) an example of bluff topography and the proximity of tree-ring samples to conical, linear, and effigy mounds located on the property.

(O'Gorman 2010). Landuse among Indigenous communities during this time included seasonal rounds and resource procurement that included the intentional use of fire to manage the land for myriad purposes (McClain et al. 2021). By 1600–1700 CE Protohistoic Oneota communities had their first encounters with French trappers and traders, and many Oneota people began migrating west in pursuit of bison herds (Boszhardt 1994). From the 1700s through the 1800s and into the onset of European colonization, many Native Nations lived on and engaged with the lands in and around Eagle Valley, including the Ioway, Ho-Chunk, Sac and Fox, Dakota, and member bands of the Three Fires Council, including the Ojibwe, Odawa, and Potawatomi. The Second Treaty of Prairie du Chien, signed in 1829 by representatives of the Three Fires Council and United States, ceded the lands that include Eagle Valley to the United States (Kappler 1904).

Twentieth Century Land Management

Current land management practices at EVNP were established in the late 1980s and emphasize actions that preserve the historical character and ecological relationships of regional native plant communities. These actions include prescribed burns in prairie and woodland settings, mechanical thinning of woody vegetation and eradication of invasive species, and some herbicide treatment of invasive species such as garlic mustard (*Alliaria petiolate*). Additionally, the mature forest and steep slopes of Eagle Valley are used as a communal night roost for wintering eagles, primarily bald eagles (*Haliaeetus leucocephalus*) as well as some golden eagles (*Aquila chrysaetos*). Prior to the establishment of EVNP and within European history on the site, the land of Eagle Valley was likely exploited for lead mining and timber in the early 1800s, followed by a transition to primarily agricultural landuse. Oral history shared by local residents suggests that some of the earliest European homes were constructed in the mid-1850s, with farming focused primarily on crops such as corn, oats, alfalfa, and, in the earlier days, clover and timothy. Cattle were pastured wherever the grade was not too steep, and hogs were grazed on the steep-sided slopes of the valley where cattle refused to go. Changing agricultural practices across the region led to a growing emphasis on row crops with a diminished emphasis on grazing over the early 1900s, with some of the smaller parcels owned by the earlier occupants used primarily for wood cutting for heating and building.

Tree-Ring Records

Given their association with pre-European vegetation and possibility of providing multi-century records of growth and environmental change, we scouted the full extent of EVNP to identify old-growth oak and eastern redcedar trees whose rings might provide insight to forest growth and change. Trees were georeferenced if they exhibited growth characteristics of old age including oak trees with thick and spreading branches indicative of being open-grown, cedar trees with strip bark and flattened canopies (Pederson 2010), and cedar stumps and remnants that exhibited deep weathering and in many cases char from past fires (Supplemental Figure S4). Sample collection occurred during the summer and fall of 2020, with cedars sampled primarily during June and July and oaks being sampled in October, after concerns for oak wilt had passed. Each sampled tree was georeferenced, photographed, and inventoried by species, vitality, and diameter at breast height. Core samples were collected along at least two radii of all living trees using a Swedish increment borer. Cross sections were collected from all cedar stumps and remnants using a handsaw to obtain the largest possible surface for tree-ring analysis.

Tree-ring samples were air-dried, mounted on wooden core mounts, and successively sanded from 40-grit to 600-grit to obtain a surface that allowed for anatomical analysis to identify annual growth-ring boundaries. This was particularly important for eastern redcedar samples that often included intra-annual variations in xylem cell size and density caused by seasonal weather conditions (Schweingruber 1996; Edmondson 2010). Crossdating, the process of assigning exact calendar dates to annual growth rings through qualitative and statistical matching of growth patterns (Douglass 1941), was accomplished by developing local master chronologies for each species and was verified against previously developed regional oak and cedar chronologies (Larson et al. 2021). This process ensured absolute accuracy in the tree-ring data and enabled the inclusion of samples collected from long-dead trees, thus producing the longest records of tree growth possible.

The tree-ring records for each species were examined in terms of age structure and mean growth rates over time to identify potential landuse and forest clearance impacts. The age structure data were visualized as vectors indicating the temporal extent of all dated samples and mapped to depict spatial patterns in tree demographics. Tree-growth patterns were analyzed using a release-detection algorithm to identify growth patterns related to canopy disturbances and/or forest clearance (Nowacki and Abrams 1997). The criteria used to identify growth releases considered two sequential 10 y windows that were shifted year-by-year throughout the entire measurement series. Release events were identified where mean ring width in the second window was 150% of that in the first window for at least 5 y in a row. In closed-canopy forests, these criteria have been determined to generally indicate increased sunlight and resource availability related to reduced competition resulting from canopy damage to neighboring trees. The release criteria were applied to the raw ring-width series using the *growthAveragingALL()* function in the *TRADER* package for the computer program R (Altman et al. 2014). Releases were summed by 5 y bins and compared to the age structure and mean chronologies for each species.

Climate–Tree Growth Analyses

Climate–tree growth relationships were quantified by comparing standardized ring-width index (RWI) chronologies to instrumental records of temperature, precipitation, and drought. Two chronologies were used in these analyses: (1) an oak chronology that included both bur and white oak ring width data and (2) an eastern redcedar chronology. The bur oak and white oak measurement data were combined based on similar crossdating patterns and past research indicating a common growth response for these species (Duvick and Blasing 1981; Larson et al. 2021). RWI chronologies were created by first removing the age-related growth trend of each measurement series by fitting a smoothing spline with 50% frequency cutoff at a 32 y frequency to each raw measurement series and dividing each year of growth by that predicted by the spline, then calculating a robust biweight mean of all RWI values for each year of tree-ring data (Cook and Peters 1981). This approach to standardization removed variability in tree growth most likely related to age-related growth trends and stand dynamics to better isolate growth patterns resulting from inter-annual to decadal variability in climate. Standardization of the ring width series and chronology development was completed using the *dplR* package for R (Bunn 2008; R Development Core Team 2019).

The resulting RWI chronologies were compared to a suite of monthly temperature, precipitation, and drought time series using correlation analysis to quantify the relationship between

Table 1.—Historical aerial imagery used to document landcover change at Eagle Valley.

Year	Date	Publisher	Source*	Format†	Color format	Scale	Image mosaicking required	Cropping required	Georeferencing required
1940	9 Oct	USDA	WHAIF	APP	B&W	1:20,000	Yes	Yes	Yes
1949	31 Oct	USDA	Arther H Robinson Map Library	APP	B&W	1:20,000	Yes	Yes	Yes
1955	8 Oct	USDA	Arther H Robinson Map Library	APP	B&W	1:20,000	Yes	Yes	Yes
1967	25 Sep	USDA	Arther H Robinson Map Library	APP	B&W	1:20,000	Yes	Yes	Yes
1974	14 Sep	USDA	Arther H Robinson Map Library	APP	B&W	1:40,000	No	Yes	Yes
1986	17 Jul	USGS	EarthExplorer	NHAP	Color Infrared	1:58,000	Yes	Yes	Yes
1995	28 Apr	USGS	EarthExplorer	DOQ	B&W	1 m	Yes	Yes	Yes
2005	17 Jun	USDA	EarthExplorer	NAIP	Color	1 m	No	Yes	No
2019	26 Sep	USDA	EarthExplorer	NAIP	Color	0.6 m	Yes	Yes	No

* WHAIF = Wisconsin Historic Aerial Image Finder.
† APP = Aerial photograph program; NHAP = National High-Altitude Photography; DOQ = Digital Orthophoto quadrangle; NAIP = National Agricultural Imagery Program.

climate and tree growth over the instrumental record (Fritts 1976). Correlations were calculated both over the full overlap of each record as well as moving 40 y windows, overlapped by 10 y, to examine the temporal stability of the climate–tree growth relationships for each species. Partial correlations were used to identify the strongest seasonal window within the climate response of both species following the methods of Meko et al. (2011). Two sets of climate data were used in our analyses: the first for the city of Guttenberg, Iowa, that spanned 1932–2020, accessed through the U.S. National Historical Climatology Network (USHCN 2019), and the second for Wisconsin Climate Division 7 that spanned 1895–2018, from the National Climatic Data Center (NCDC 2017). The Guttenberg dataset was the closest weather station, being just across the Mississippi River, however, missing data in the observations led to the use of the NCDC divisional data set instead to provide complete data and enable a longer-term comparison between tree-growth and climate.

Based on the results of our climate-tree growth analyses, we developed a linear regression-based reconstruction of Palmer's Drought Severity Index (PDSI), a commonly used metric of available soil moisture (Palmer 1965), based on the RWI chronologies of both the cedars and oaks sampled at Eagle Valley. The reconstruction employed a split-calibration approach to develop a multi-species multiple linear regression based on the RWI chronologies for both oak and cedars. This entailed calibration of a regression on the first half of the climate and tree-ring data that was then verified by modeling the second half of the dataset that had been withheld from the calibration. This process was then reversed, with calibration of the regression based on the latter half of the climate and tree-ring data and verified on the first half of the data set. Successful calibration and verification for both splits indicates a consistent relationship between climate and tree growth over time and helps justify the reconstruction (Fritts 1976). Verification and reconstruction skill were based on the reduction of error (RE) and coefficient of efficiency (CE) statistics from the split calibration and the coefficient of regression (r^2). The reconstruction was then compared to instrumental records for the site to help determine if current moisture conditions at Eagle Valley are within the historical range of variability for the site.

Landcover Change

We quantified changes in landcover area and spatial configuration at Eagle Valley using historical aerial imagery and spatial analysis software. Aerial photographs for the property were obtained from the University of Wisconsin Robinson Map Library and georectified in ArcGIS Pro 2.4 using 2019 imagery as reference and using at least 20 landmarks evident in both the historical and modern imagery as control points. Image years included 1940, 1949, 1955, 1961, 1974, 1983, 1993, and 2000 (Table 1); where multiple images from the same series were used, we first cropped and mosaicked the images in Adobe Photoshop 2021, rather than GIS, to avoid automatically applying a projection in the output. Landmarks used in the georeferencing process included built structures, road intersections, features of Lock and Dam #10 on the Mississippi River, and other cultural features. During the georeferencing process, we used the transformation that produced the best image alignment as verified through visual inspection and the nearest-neighbor resampling technique to avoid altering original data values as much as possible. All images were projected to North American Data 1983 HARN Wisconsin TM with a 1 m spatial resolution. Although we minimized error and maximized alignment across the images, we report slight mismatch (<10 m) in some portions of some images as a result of a lack of identifiable locations for ground control points. This error, however, was not large enough to affect the broader trends in landscape change.

We considered several approaches to classifying historical landcover conditions, including an automated vs. manual approach to landcover classification, and a variety of landcover classifications. Due to the relatively small total area considered in this study, variability in the resolution of the available images, time of day that images were acquired, and seasonality of the images, we chose to manually delineate the landscape by digitizing polygons of three distinct landcover classes: (1) open (e.g., fields and grasslands), (2) forested, or (3) developed (e.g., large roads, buildings, and houses). Patches of each landcover type were delineated using the Split and Streaming tools in ArcGIS Pro. Map topology and snapping were enabled to ensure data integrity. All polygon feature classes were exported as 1 m resolution raster images for spatial analysis.

Landscape patterns and change were quantified at the scale of the entire property (i.e., landscape scale) and by landcover type

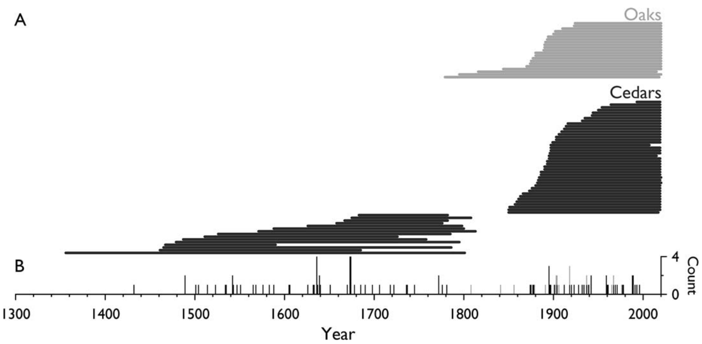

Figure 2.—Tree-ring data collected from oak and cedar trees sampled at Eagle Valley, displayed as (A) lines representing the temporal extent of each sample and (B) release events identified as sudden and marked increases in ring width (see Methods for details). Distinctive features of the data include remnant cedars dating to the 1300s and 1400s, a few of the oldest oaks dating to the late 1700s, a distinct gap in the cedar tree-ring data from 1813–1850, and a pulse of establishment for both oaks and cedars in the mid- to late-1800s. Other than two surges in ring width shared by four cedars, each in the 1600s, release events suggest relatively infrequent canopy disturbance events across the site, with a cluster of releases in the early 1900s and again in the late 1900s potentially indicating shifting landuse patterns.

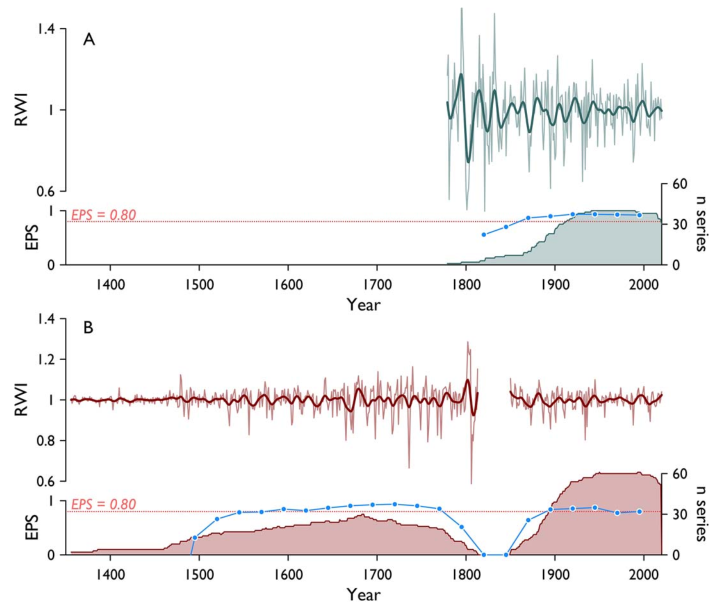

Figure 3.—Ring-width index (RWI) chronologies for (A) bur and white oak trees and (B) eastern redcedar trees sampled at Eagle Valley. Each set of graphs include the mean RWI chronology time series represented as a thin line for interannual values and a bold line showing an 11 y smoothing spline of each chronology. The number of measurement series in each chronology over time is shown as a filled line graph, and the expressed population signal (EPS) as a line graph relative to the critical threshold of 0.8 to indicate the strength of the shared signal in the chronology over time (Wigley et al. 1984).

(i.e., class). The specific metrics calculated for each year of imagery included: (L1) the total number of distinct habitat patches in the study area, (L2) the mean patch area, (L3) the density of patch edges on the landscape, (L4) the landscape shape index, which is a measure of the complexity of patch shapes, (C1) the number of patches of each cover type, (C2) the proportion of the study area in each cover type, (C3) the mean patch area by cover type, (C4) the largest patch index by cover type, a measure of landscape dominance, and (C5) the landscape shape index by cover type. We analyzed the classified raster images in Fragstats 4.2 (McGarigal et al. 2002).

In addition to the quantitative landcover change analysis we obtained historical records that described the environmental history of the site, including a hand-drawn and georeferenced map published in 1838 and based on interpretation of the Public Land Survey record field notes, the original General Land Office (GLO) survey notes available from the Wisconsin Board of Commissions of Public Lands (accessed 2 August 2023 from http://digicoll.library.wisc.edu/SurveyNotes/SurveyNotesHome.html), and a digitized historical atlas of mining activity in Wisconsin (Pepp et al. 2019).

RESULTS

Tree-Ring Data

We collected increment core samples from a total of 92 trees, including 42 living eastern redcedars (hereinafter "cedars"), 28 dead cedars, 20 living oaks, and 2 dead oaks (Figure 2A). Among the oaks, 13 were white oak and 9 were bur oak. The distribution of sampled trees was primarily along the side slopes of Eagle Ridge, with most cedars sampled among rock outcrops overlooking the Mississippi River and oaks along the side slopes and nearer to the top of the ridge. Crossdating was achieved for all samples collected from living trees for both species and for 15 of the 28 cedar cross sections. The 13 undated cedar samples contained either too few growth rings to confidently date or were complacent, meaning they lacked sufficient variability in ring width to confidently align with other samples. Mean inter-series correlation was 0.489 among the oak ring-width series and 0.524 among the redcedar ring-width series, indicating robust crossdating for both species. Growth rings of the oak samples spanned 1779–2020, with a steep increase in sample depth beginning in the 1850s (Figure 2A). The temporal span of tree-ring data from the living cedars was 1850–2020, with many of the oldest living cedars establishing in the mid-1800s (Figure 2A). Crossdating among the samples from cedar remnants that dated was excellent, but no link to the living chronology was apparent, resulting in a 457 y floating chronology. Crossdating was accomplished using an eastern redcedar chronology previously developed at Devil's Lake State Park (Federman et al. 2019). The floating chronology was thus anchored to a time span of 1356–1813, with almost all trees exhibiting evidence of having been cut in the early 1800s (Figure 2A). Analyses of growth patterns identified 94 release events recorded by cedars, and 17 recorded by oaks. Relative to the time span and sample depth, release events were rarely recorded by more than a single tree in any particular year and occurred sporadically through time (Figure 2B).

Climate–Tree Growth Analyses

The shared growth patterns represented by the RWI chronologies for both species convey a multi-century perspective on tree growth at Eagle Valley. Sample size and the expressed population signal (EPS) (Wigley et al. 1984) indicated robust chronologies for the oak from 1846–2020 (Figure 3A) and cedar from 1546–1795 and 1871–2020 (Figure 3B). Both species exhibited similar variability over their common period, with a Pearson product moment correlation between the chronologies of 0.58 indicating substantial shared high-frequency variability but distinct signals none the less.

Comparing the RWI chronologies for both chronologies to climate identified moisture-sensitive growth responses, including positive correlations with precipitation, and inverse correlations with temperature. Missing observations early in the Guttenberg climate record limited comparisons to those data to 1950–2020. The oak RWI chronology was positively correlated with April–July precipitation and inversely correlated with January, March, and April temperatures of the current year, positively correlated with previous year September and December precipitation, and inversely correlated with previous year July and August temperatures (data not shown; see results from divisional data in Figure 4B). The cedar climate response exhibited a broadly similar signal but captured a different seasonal window. Correlation of the cedar RWI chronology identified significant positive relationships with June and July precipitation, significant inverse relationships with May, July, and August maximum temperatures of the current growing season, and a significant inverse relationship with July temperatures of the previous year (see Figure 4B).

Comparison with Wisconsin Division 7 climate data identified a similar response for both species to that identified with the Guttenberg climate data, including positive correlations with precipitation and negative correlations with maximum temperatures during the growing season (Figures 4A and 4B). Overall, oak growth was more sensitive to precipitation and cedar growth was more sensitive to temperature. Together, these factors represent the shared influence of temperature and precipitation on soil moisture conditions, and, accordingly, the strongest climate–tree growth relationships identified were relative to Wisconsin Division 7 PDSI. The oak chronology exhibited a relatively consistent response to climate over time, while moving correlations indicated a dampened response to drought by cedars during the mid-1900s (Figures 4C and 4D). Focusing on the PDSI signal, partial correlations indicated the peak seasonal correlation with the oak chronology was for the 5 mo period of May–September for the current growing season. The strongest seasonal correlation with cedars was for the 4 mo of May–August of the current growing season.

Exploratory analyses based on the climate response and partial correlations focused our reconstruction effort on mean May–September PDSI, essentially the growing season. Split calibration and verification indicated a skillful reconstruction, with RE and CE metrics for both splits higher than the key threshold of zero (Table 2) (Cook and Kairiukstis 1990). The final reconstruction explained 42% of instrumental May–September PDSI (Figure 5). The reconstruction captured several distinct climatic events including the droughts of 1895, 1910–11, the Dust Bowl drought years of 1931, 1934, and 1936, and other severe droughts in 1956 and 1988–89. As is often the case, the reconstruction did not represent extreme wet conditions as accurately as droughts (Wise and Dannenberg 2019), but did accurately represent the wet years of 1903, 1908, 1951, 1973, and 1993. The reconstruction also missed some key drought events, including in 1923, 1930, 1963, and 1964, suggesting that the site-specific conditions at Eagle Valley have differed from regional conditions or that factors other than growing season soil moisture influenced tree growth more strongly during those years.

The value of the resulting reconstruction is limited in terms of paleoclimate information simply because of the relatively short period covered by the anchored chronologies. Where the reconstruction provides key insight is examination of the skill of the reconstruction over the full instrumental record. Importantly, while the reconstruction is skillful, meaning that it provides more information about past conditions than would be available using the mean of the instrumental period, Durbin-Watson Tests for both sides of the split calibration indicated significant autocorrelation in the regression residuals (Table 2). This indicates that a trend exists in the residuals and that the reconstruction is less accurate over time. This pattern of increasing residuals in the reconstruction is clearly illustrated when both time series are smoothed, which emphasizes an increasing underestimation of soil moisture conditions over recent decades (Figure 5).

Land Cover Change

Aerial imagery included nine series that spanned the years 1940–2019 and illustrated patterns of vegetation change at Eagle Valley that are common across the Driftless Region over this time. Overall, the images document the ingrowth of trees onto previously open sites (examples indicated with asterisks in Figure 6A), closure of previously open forest canopies (examples indicated with plus signs in Figure 6A), and an increasingly homogeneous forest cover (examples indicated by circumflex symbols in Figure 6A). Focusing on specific locations further illustrates some of these changes. Infill, canopy closure, and landcover homogenization are clearly evident in and around several goat prairies and fields that exist along the west-facing bluffs of Eagle Ridge overlooking the Mississippi, particularly just north of a mound complex along the southern extent of the ridge (Figure 6B). This suggests that despite intensive management and restoration activities in this area since the 1980s, ecological inertia and climate are driving an overall closure of the landscape. Similarly, and potentially more dramatically, forest development around the house and preserve facilities represents a wholesale change in landcover and floristic assemblage (Figure 6C). Prior to the preserve being established, this was the farm homestead and these changes appear to have accelerated after the 1970s with the removal of cattle and associated grazing pressure from the landscape (Figure 6C) (Brown et al. 2003).

Quantification of landscape patterns supported this visual interpretation and described a shift from a landscape of mixed forest and openings to a primarily forested landscape with an overall reduction in the complexity of landscape patterns. At the landscape scale, a total of 99 distinct patches were evident in the 1940 imagery, which increased to 110 in 1955, and declined to 28 by 2019 (Figure 7A). Mean patch area increased from 5.8 ha to 20.6 ha (Figure 7A), while edge density and the landscape shape index decreased over this period (Figure 7A). At the scale of cover

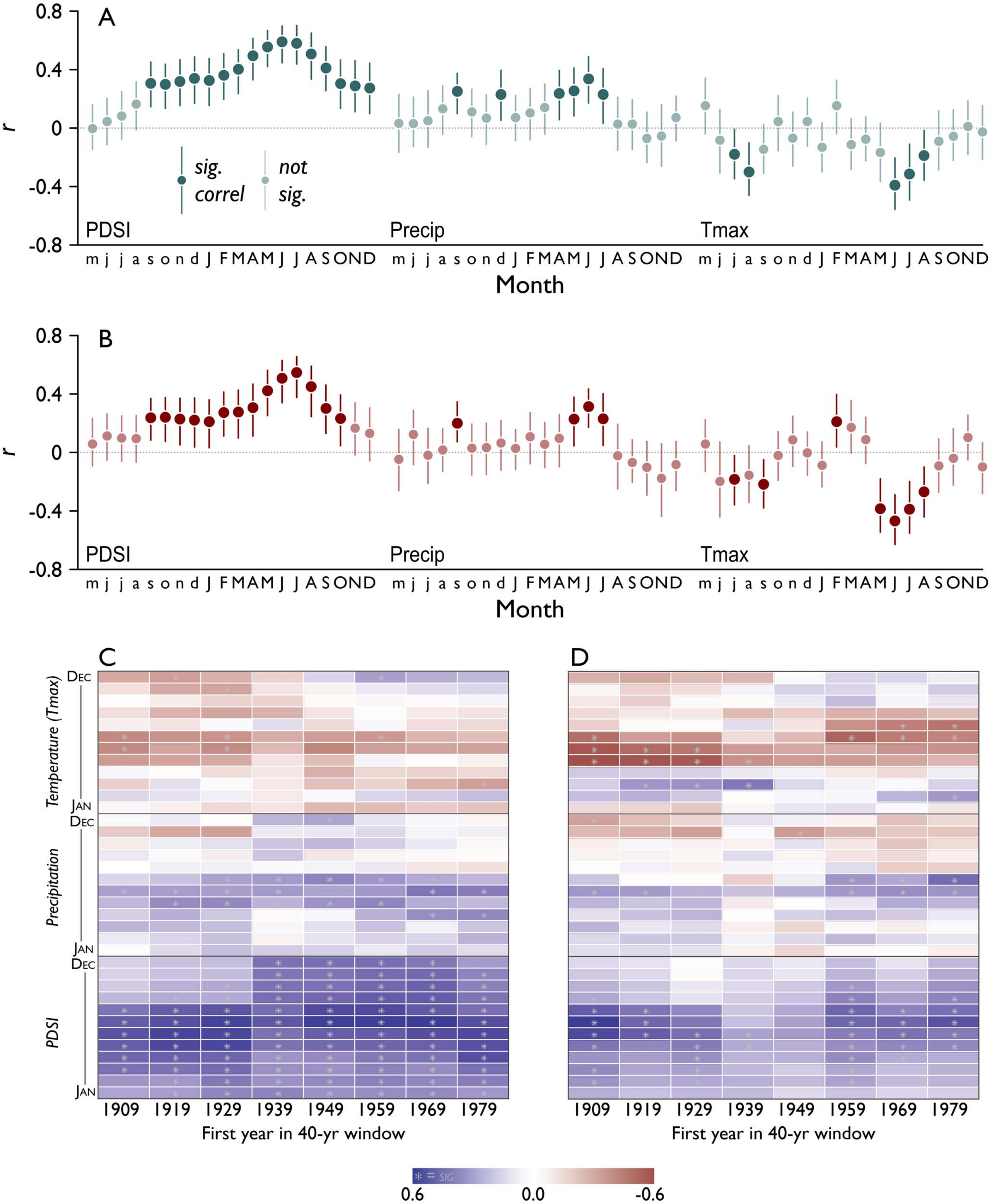

Figure 4.—The climate–tree growth relationships exhibited by the oak and cedar RWI chronologies relative to NCDC Wisconsin Climate Division 7 data. The climate response for the period 1895–2018 is shown as Pearson Product-moment correlation coefficients (r) between RWI chronologies and PDSI, precipitation, and maximum monthly temperatures from May of the previous year through the current December for (A) oaks and (B) cedar. Correlations of the same variables over moving 40 y windows, overlapped 10 y, indicate some change in climate–tree growth relationships over time for both (C) oaks and (D) cedars, but a consistent overall seasonal response.

Table 2.—Calibration and verification statistics for a reconstruction of May–September Palmer's Drought Severity Index (PDSI) for National Climatic Data Center Wisconsin Division 7. The statistics reported are based on a split calibration and include the coefficient of determination (r^2), reduction of error (RE), coefficient of efficiency (CE), root-mean-square error (RMSE), and the Durbin-Watson *d* statistic (D-W *d*; a measure of autocorrelation in the residuals of a regression) (Fritts 1976).

Calibration period	r^2	RE	CE	RMSE	D-W *d*
Early (1895–1959)	0.49	0.32	0.19	0.83	1.59*
Late (1960–2018)	0.40	0.19	0.07	0.75	1.47*

* $P < 0.05$.

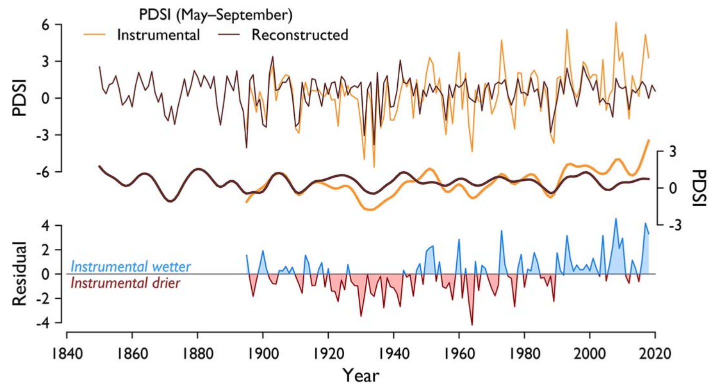

Figure 5.—Instrumental and reconstructed May–September PDSI as interannual values (top), filtered using an 11 y smoothing spline (middle), and as regression residuals (bottom). Overall patterns of interannual- to decadal-scale variability match for most of the records, but increasingly positive residuals over recent decades indicate consistently wetter conditions than represented over the full extent of the tree-ring record.

type, the number of patches declined for all classes while mean patch area increased (Figure 7B). The proportion of developed land increased marginally from 0.7% to 1.0%, while forest cover increased from 60.7% to 82.9% and open areas declined from 38.5% to 16.2% of the landscape (Figure 7B). The mean area of forest patches increased substantially over this time and increased only slightly for open areas and developed land. The largest patch index depicted an increase in dominance by forests, while the landscape shape index for each cover type declined, indicating an overall simplification of landscape pattern (Figure 7B).

DISCUSSION

Contextualizing Landscape Change with Tree Rings and Historical Records

The tree-ring records developed at Eagle Valley provide a framework to examine documented and anecdotal history to understand both how the landscape has changed and why those changes occurred. Patterns of tree establishment indicate a prolonged relationship between people and the ecological communities of this region. The earliest establishment dates of eastern redcedar trees, determined from stumps, were in the 1300s and 1400s and fall shortly after archaeological evidence suggests a significant shift in social structure and subsistence practices among the mound-building cultures of the upper Mississippi and Ohio River Valleys (Benson et al. 2009). In particular, changing social structures and power relationships coupled with a shift in climate contributed to a decline in the construction of earth mounds and other monuments, with the eventual dispersal of the population at Cahokia in the 1300s, far to the south of the study area but often considered the center of the Upper Mississippian culture from ca. 1000–1350 CE (Trubitt 2000; Muñoz et al. 2015). An additional factor driving cultural change in and around the Driftless Region at this time may also have been resource scarcity, specifically a lack of fuel wood driven by increasing human population and use (Theler and Boszhardt 2006). The mounds at Eagle Valley are poignant evidence of how people fundamentally shaped the landscape over the past millennium, and the establishment dates of eastern redcedars, a species known for colonizing recently abandoned open areas, suggests that these could have been among the first generations of trees to establish on what was undoubtedly a more open landscape since the emergence of mound-building culture at the site. Notably, the sampled cedar stumps indicated that the trees cut from the landscape in the early 1800s were of exceptional age despite their relatively small size (Figure 8), emphasizing the harsh growing conditions in which they existed (Schulman 1954) and highlighting the potential for developing additional long tree-ring chronologies at other sites throughout the Driftless Region, where this species is often found inhabiting rock outcrops and bluffs. Further examination of the ages of eastern redcedar trees and stumps along the Mississippi River and its tributaries could elucidate the possibility of a post–mound building era cohort of tree establishment, similar to that documented among the fire-shaped forests of the Jemez Plateau in the American Southwest following the abandonment of certain pueblos (Liebmann et al. 2016). This line of inquiry is worth further investigation.

Events become more certain closer in time to the present. The establishment of both cedars and oaks during the mid-1800s is a phenomenon observed across southwest Wisconsin (Larson et al. 2021). This period of widespread tree establishment is linked to declines in fire activity with the cultural disruption and often violent dispossession of Indigenous peoples that produced traumatic changes in land relationships and was coupled with spreading agricultural practices that effectively eliminated the role of fire in maintaining the prairies and open oak woodlands and savannas that were common to the area. The surge in tree establishment associated with these changes was noted by Aldo Leopold in the "Bur Oak" section of *A Sand County Almanac* (1949), among others. The forests of Eagle Valley, even including many of the open-grown oaks found on the land today, are a product of landscape changes driven by massive social and ecological shifts over the 1800s. The infrequent canopy disturbance events during this time, identified by patterns of ring-width, are indicative of an open forest where relatively few canopy disturbance events occurred (Lorimer and Frelich 1989), even while the recent landscape is moving toward closed-canopy conditions. A general lack of pit-mound topography observed across the study area, which entails microtopographic features associated with long-term forest cover and the influences of

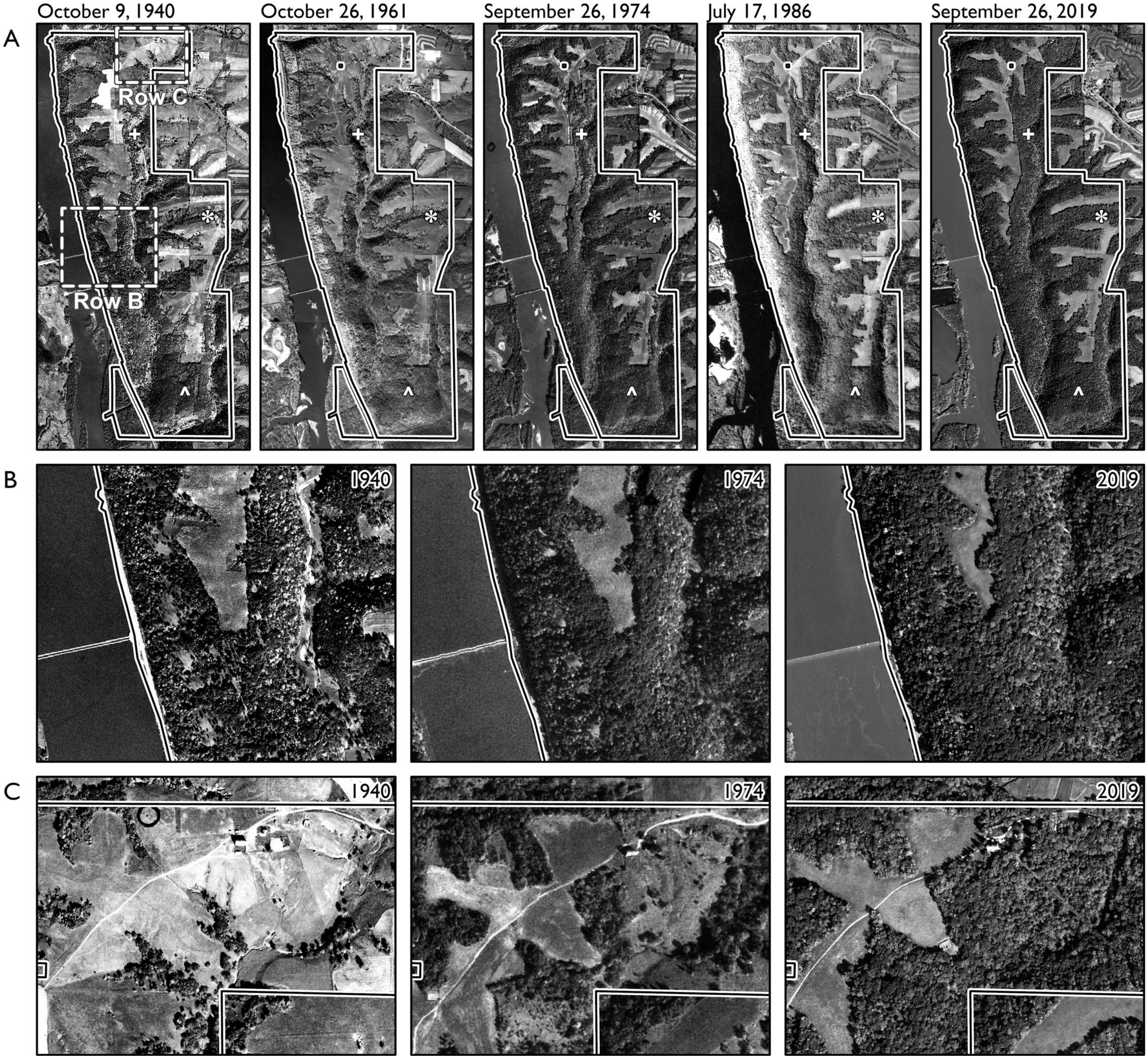

Figure 6.—Historical aerial photographs of Eagle Valley illustrating landcover change over time. The series of photographs shown in row (A) span the years 1940–2019 and were taken at roughly the same time of year. Annotations include extent indicators for the images shown in rows (B) and (C), as well as asterisks (*) to draw attention to an example of where trees have invaded previously open sites, plus signs (+) indicating an example of forest canopy closure, and circumflex symbols (^) indicating increased forest cover homogeneity. Other photo series were excluded from this visual comparison due to differences in seasonal timing of the images but were included in the quantitative comparison. Row B illustrates landcover changes over this time period near some of the goat prairies that are a focus of current management efforts. Row C depicts landcover change near the house and barn.

windthrow that is common in closed-canopy forests (Schaetzl and Follmer 1990; Wessels 1997), suggests that the closed-canopy forest across much of Eagle Valley represents the first time such conditions have occurred in a millennium.

The establishment of oaks in the late 1700s and into the 1800s aligns with early descriptions of the area, including those of Rowland Hall and Enos Burdino, the surveyors hired by the General Land Office who, in April of 1832, surveyed the lands on which Eagle Valley is located (Supplemental Figure S5). The surveyors frequently noted the rolling hills, excellent soil, "thinly timbered by oak" when describing the lands around the property. Describing the section line that crossed Eagle Valley, they recognized the rugged terrain by stating "Land broken by hills and ravines – good soil. Well timbered with

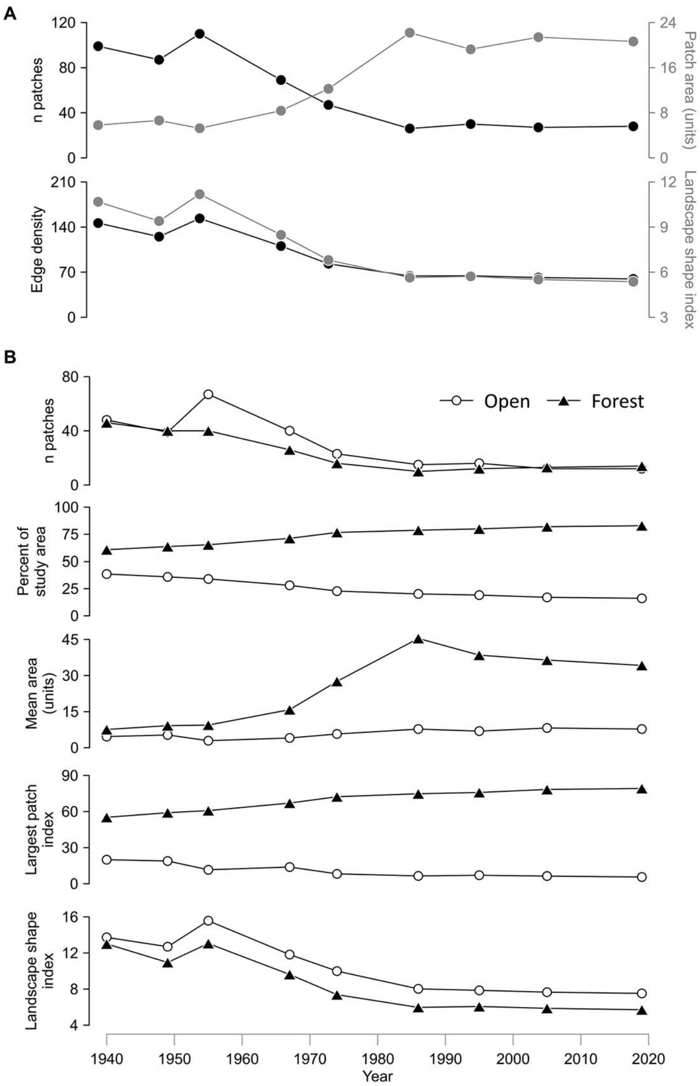

Figure 7.—Landscape metrics describing patterns in landcover change over time at the (A) landscape scale and (B) by landcover type.

w. oak." Survey notes and bearing tree records of the General Land Office Survey have been used in combination with modern computers, GIS, and modeling efforts to describe much of the vegetation in this region as mixed oak savanna and oak woodland (Schulte and Mladenoff 2001), however an earlier hand-drawn effort that employed largely the same methods in a less technical manner presents a less detailed but no less interesting depiction of the generally open vegetation communities of the time, while clearly depicting the already emerging European cultural landscape at the time (Figure 9A; Taylor 1838). Another historical map of the lead mining district of the Upper Mississippi River published in 1829 includes text in the margin stating that "Miners are entitled to the free use of timber for building and [to] fuel smelters" and that "Farming is permitted free of rent, wherever it can be done without interfering with the timber needed for mining purposes" (Supplemental Figure S6; Chandler 1829). In other words, miners had an unrestricted freedom of action on the land *before* the GLO surveys were conducted in Wisconsin.

Our results suggest that interpretations of vegetation communities in this region based on GLO survey records should be viewed with some caution if used to represent the pre-European landscape. The cut cedar stumps scattered across the property, all with outer rings in the early 1800s, are evidence of land clearance and timber harvesting during the earliest onset of European lead mining in the region (Chandler 1829). Based on the relatively small size and twisted morphology of these stumps, it is unlikely that these trees were straight enough or tall enough to be harvested for construction of dwellings. Instead, it seems likely that these trees were harvested for use as fence posts or in early mining efforts. A recently published atlas of historical mining activity in Wisconsin indicates multiple locations of surface mining within the boundaries of Eagle Valley (Figure 9B; Pepp et al. 2019). Unfortunately, the effort did not digitize the records for the southern extent of the property where multiple crude mine shafts are located (Figure 9C). The outer dates of the cedar stumps suggest creation of these mines in the first two decades of the 1800s, placing their development at the very earliest stages of the lead mining period. The cedar stumps, then, provide clear evidence of landuse impacts that pre-date the 1832 General Land Office surveys of the land now known as Eagle Valley. The indication of widespread lead mining activities in the 1838 map, along with a network of trails and houses, implicitly reinforces this point. The most important implication from these results for the stewardship of Eagle Valley and elsewhere in the region is to acknowledge that while the GLO survey records do represent vegetation patterns of a landscape *less* impacted by European agriculture and landuse, they do not represent the idealized and problematic steady-state pre-European landscape that can at times shape perspectives of restoration activities (Higgs et al. 2014).

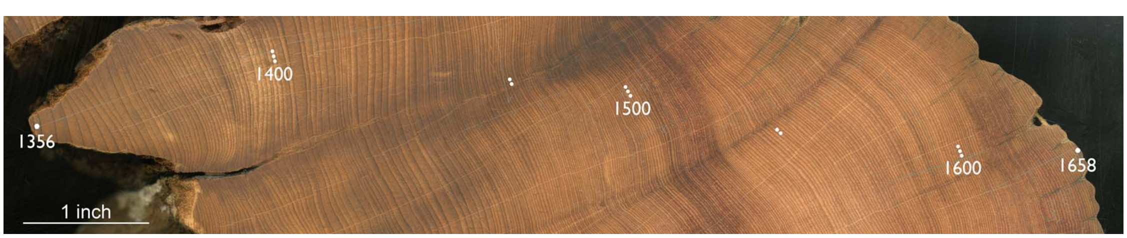

Figure 8.—The scanned surface of sample EVC027 with growth rings that date from 1356 to 1658. Single dots mark the innermost and outermost rings, two dots indicate mid-century marks, and three dots indicate the centuries. Note the scale bar in the lower left corner of the image.

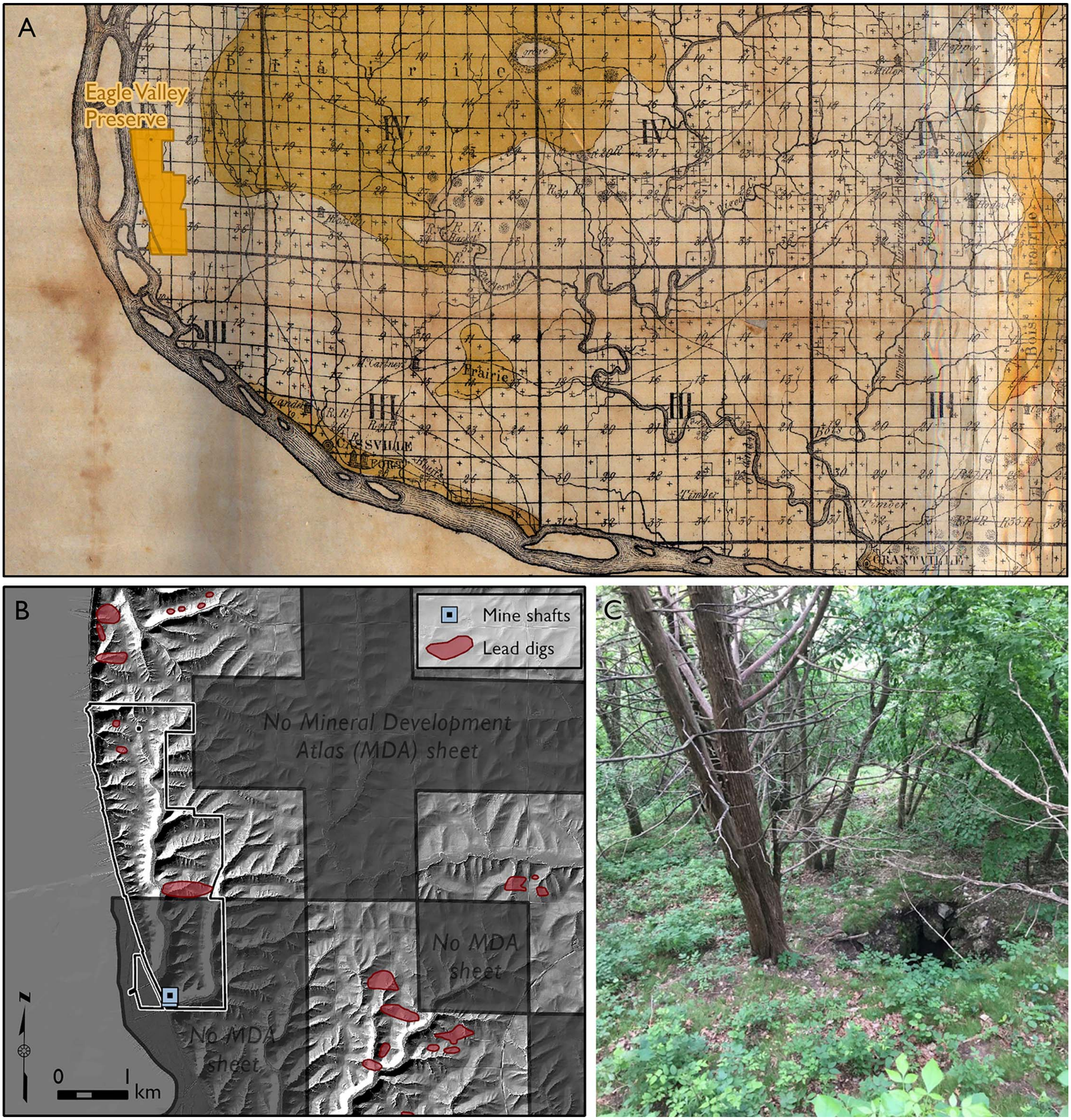

Figure 9.—Historical and contemporary evidence of mining activity in and around Eagle Valley including (A) an excerpt from a hand-drawn map derived from GLO surveys and published in 1838 (Taylor 1838), with prairies represented by yellow shading and locations of lead mining activity indicated by stippling, (B) digital mining records from a recently published atlas of historic mining activities in southwest Wisconsin (Pepp et al. 2019), and (C) onsite evidence including multiple mine shafts found on the slopes above the intersection of Good 'Nuf Hollow road and Closing Dam road.

Factors Driving Ecological Change

The changes in landcover observed over recent decades and described here through interpretation of tree-ring data and historical documents depict a landscape that, for at least the past 150 y and possibly for multiple centuries, has been shifting toward more closed-canopy forests in most areas where fire has been removed and agriculture does not maintain open grown annual crops or pasture (Nuzzo 1986). The paintings of George

Catlin, who traveled up the Mississippi River in the 1830s, depict an immensely open landscape with scattered trees amid what appear to be grass-covered hills at multiple sites within close proximity of Eagle Valley (Figure 10). Some estimates of past fire occurrence have been developed by documenting fire scars in the growth rings of pre-settlement oak trees (Wolf 2004), but no fire scars were identified in our tree-ring samples and no such records exist for southwest Wisconsin. Recent efforts have developed tree-ring-based fire histories from the rings of red and white pine trees (*Pinus resinosa* and *P. strobus*) growing in pockets set within the matrix of prairie and hardwood forests of the Driftless Region (Larson and Green 2017; Meunier et al. 2019), and indicate fire frequencies of 2–4 y were common at many sites. Abundant evidence in traditional knowledge and historical records indicate that people have been a key driver of ignition patterns among Midwestern prairies for centuries to millennia (Lake and Christianson 2019; McClain et al. 2021). Disruption of this relationship is a primary contributor to landscape change at Eagle Valley, with the effects of altered fire regimes expressed in vegetation changes documented across the region (Knoot et al. 2015).

In addition to changing disturbance regimes, climate at Eagle Valley has changed over the past century with an emergent trend toward higher moisture availability over the past three decades than at any time in either the instrumental record of PDSI or the tree-ring-based reconstruction. The deterioration of the climate–tree growth relationships observed at Eagle Valley is similar to that observed across the upper Midwest, and may be the expression of increasing wet conditions that are unprecedented in the historical record (Maxwell et al. 2016). These observed changes align with the projected impacts of human-driven climate change in the Upper Midwestern United States (Marvel et al. 2023). Given the strong influence that moisture availability has on plant productivity and dry prairie community structure (Cleland et al. 2013), this increased amount of available moisture has very likely altered species interactions and growth dynamics. Essentially, more moisture likely shifts site conditions to be more suitable to closed-canopy forests than open prairie or savanna habitats, amplifying and reinforcing the already occurring impacts of vegetation-driven mesophication resulting from altered fire regimes (Nowacki and Abrams 2008). Relative to the environmental gradients that help determine the location of the prairie forest border (Frelich and Reich 2010), wetter conditions therefore likely contribute to meadow encroachment by facilitating tree seedling survival (e.g., Brown and Wu 2005) and increased tree growth to accelerate canopy closure.

While scholarly debate continues on the relative roles of fire and climate in driving observed changes in vegetation communities across eastern North America (Nowacki and Abrams 2015; Pederson et al. 2015), it may be instructive to consider the increasing trend in moisture availability as one of many contributing factors to the ratchet of historical events driving vegetation change from prairie to forest, thus building on decades of fire suppression and the onset of woody plant encroachment to set the stage for rapid ecological change (Jackson et al. 2009). Indeed, the changes observed in the aerial imagery indicate an acceleration of forest development following the 1970s, which coincides with this onset of the increasing moisture availability and a cessation of cattle grazing. The implications for management are that, given the species assemblage of the surrounding landscape, the low potential for lightning-caused fires, and the built-up ecological inertia of young forest, the role of engaged land stewardship at Eagle Valley, among other Midwest prairies systems, is more important now than ever if a goal of maintaining landscape diversity is pursued. If the application of fire and thinning treatments were to cease, the resulting ecological changes would be rapid and substantial. Essentially, each factor described above has compounded to prime the landscape to become a continuous, closed-canopy forest that would result in substantial declines in plant and animal diversity at the landscape scale.

CONCLUSION

The environmental history of Eagle Valley helps to situate current stewardship activities within a centuries-long socio-ecological narrative. A gradual trajectory began almost 600 y ago with the establishment of cedars among the rock outcrops of what was otherwise an open landscape. Oaks established, too, and as fires, many of which were likely associated with Indigenous landuse practices, burned across the landscape, change was relatively slow. Tree harvest during the lead mining era in the early 1800s produced a more open landscape than would otherwise have been encountered during the GLO surveys, yet was followed closely by the onset of fire exclusion and an acceleration of tree establishment that continues today. Landcover since that time has followed a trajectory of closure and declining complexity with respect to the shape of habitat patches, resulting in fewer and larger vegetation patches increasingly dominated by closed forest. These vegetation changes were likely amplified by increasing moisture availability over the last 30 y, creating a landscape of sharp contrasts between open, managed prairie, and predominantly closed-canopy forest. The gradients between the two, embodied in oak savannas, has diminished not just at Eagle Valley, but across the entire Driftless Region. Decades of restoration work and invested resources have helped to maintain and expand open prairie and woodland settings at Eagle Valley, although repeat aerial images illustrate the need to enhance and expand these efforts if management goals are to shift toward a balance between open and closed landscapes more representative of the 1800s or earlier. These transitions are vitally important for maintaining landscape diversity and resiliency. Based on the age and architecture of the trees sampled and the soil surfaces observed during fieldwork, it seems likely that the trees growing by the mounds on Eagle Ridge represent the first closed-canopy forest to grow on that site since the mounds were constructed over a millennium ago.

These results can be interpreted as evidence of overwhelming cultural, climate, and ecological momentum away from the vegetation communities of the past, with the clear implication that if management activities cease at Eagle Valley, homogenization of the landscape will occur rapidly and nearly completely. At the same time, the emerging narrative can be empowering by helping

Figure 10.—Paintings by George Catlin during his 1832 voyage up the Mississippi River including (A) *Madame Ferrebault's Prairie, above Prairie du Chien* that was painted approximately 25 km north of Eagle Valley and shows oaks scattered over open prairies, with some trees massed in ravines and at the river's edge but more rare on open slopes, and (B) *Dubuque's Grave, Upper Mississippi*, painted 50 km to the south, that depicts a similarly open landscape along with several cultural features that exist today and enable a close comparison. Images made available from the Smithsonian American Art Museum under the Creative Commons Zero License (https://americanart.si.edu/artist/george-catlin-782).

to balance questions of what is possible and what *should* be. The current ecological communities at Eagle Valley are linked through time with what came before and will be linked to what comes next. A deeper understanding of the long-term dynamics of this system that recognizes ecological communities have always been changing and that humans have likely always been a factor in these changes helps to shed the concept of "natural" as it is often applied in restoration ecology (Higgs et al. 2014), and instead offers the opportunity to move forward through a conversation with the land that balances management goals, stewardship ideals, and the environmental history and future of the land at Eagle Valley Nature Preserve.

ACKNOWLEDGMENTS

Fieldwork plans for this project were changed substantially in response to the COVID-19 pandemic, and the contributions of Mara, Bryn, and Danica Larson were key to development of the eastern redcedar chronology. Devin Drier contributed to the fieldwork for this project. Treyton Landeau and Shannon Gaul helped develop the oak tree-ring data and chronology. This research was made possible through the generous support of the Kohler Trust for Preservation.

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Brett A. Mandernack managed Kohler Co. and Kohler Trust for Preservation's Eagle Valley Nature Preserve in Southwest Wisconsin from February 1987 through early May 2023, is now semi-retired, lives on-site, and continues various multi-year raptor research projects and landscape restoration and management efforts on the preserve. He holds an MS in Biology with Wildlife emphasis and a BS in Biology, both from the University of Wisconsin-Eau Claire.

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