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Rates of Historical Anthropogenic Soil Erosion in the Midwestern United States

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Key Points:

- Escarpments have formed at the boundary between native prairies and cultivated fields in the Midwestern U.S. due to agricultural erosion
- Surveys of the escarpment heights at 20 sites indicate that the erosion rate, averaged since the time farming began, is 1.9 mm year^{-1}
- Historically averaged erosion rates exceed model predictions of present-day rates, in part because the models do not include tillage erosion

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Erosion degrades soils, reduces crop yields, and diminishes ecosystem services. The total amount of soil that has been eroded since the initiation of farming is unknown in most agricultural landscapes, which hinders assessment of soil erosion trends. In the Midwestern U.S., erosion has caused native prairie remnants to become perched above surrounding farmland, providing an opportunity to measure historical soil erosion rates. We use high-resolution topographic surveys conducted across erosional escarpments at the boundary between 20 prairies and adjacent agricultural fields and show the median reduction in soil thickness ranges from 0.04 to 0.69 m, corresponding to erosion rates of 0.2–4.3 mm year^{-1}, with a median value of 1.9 mm year^{-1}. We used an association between the measured reduction in soil thickness and topographic curvature to predict regional soil erosion integrated since the beginning of farming to the present. We estimate a median historical erosion rate of 1.8 ± 1.2 mm year^{-1}, which is nearly double the rate considered tolerable by the U.S. Department of Agriculture (USDA). Current soil loss predictions from the USDA National Resources Inventory (NRI) and the Daily Erosion Project (DEP) are lower than our historically averaged erosion rate by a factor of 3 and 8, respectively. We suggest that the NRI and the DEP underpredict soil loss rates because they do not include tillage erosion, a process shown to be important throughout the Midwestern U.S. Our findings indicate that further implementation of conservation practices is needed to reduce the high centennial-averaged soil erosion rates that we measure to sustainable levels.

Plain Language Summary The Midwestern United States is one of the world's most productive agricultural regions. However, high rates of soil erosion caused by farming have caused native prairie remnants to become perched above surrounding cultivated fields. We conducted high-resolution topographic surveys of the height of erosional escarpments at the borders of 20 native prairies and fields and used land records to estimate erosion rates that span the time since the initiation of farming to the present day. Our results indicate that soil thickness on hilltops in the Midwest has declined at an average rate of nearly 2 mm year^{-1} over the past 150 years. The historical erosion rates exceed predictions of present-day erosion rates from national soil erosion assessments and levels considered tolerable by the U.S. Department of Agriculture.

1. Introduction

Conventional agricultural practices have accelerated soil erosion rates, resulting in widespread soil degradation throughout the world's agricultural regions (Montgomery, 2007b). Soil degradation diminishes soil fertility by removing organic matter and nutrients (Pimentel, 2006), which, without countervailing practices such as fertilization and genetic crop enhancements, leads to reductions in crop yields (Lal, 2004; Tilman et al., 2002). Fertilizer use, however, does not fully restore the productivity of eroded soils (Fenton et al., 2005), and because fossil fuels are required to generate the energy required for fertilizer production, the use of fertilizers to increase yields in degraded soils is not sustainable (Montgomery, 2007a). Further, soil erosion leads to increased agricultural production costs (Pimentel et al., 1995) and negative offsite effects such as increased sedimentation and nutrient export to downstream waterbodies (Tilman et al., 2002). In the United States, recognition of the high costs of soil erosion in the early twentieth century led to the development and implementation of soil conservation practices (Bennett, 1948). Field trials have demonstrated the efficacy of soil conservation efforts (Pimentel et al., 1976; Steiner, 1987), but it is unclear whether the advent of soil conservation practices and policies has led to a reduction of region-wide soil erosion rates in the U.S.

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Here, we measure the reduction in soil thickness within agricultural fields that has been caused by conventional farming activities. Soil erosion processes cause the decrease in soil thickness, and we equate the rate that the soil thickness has declined to a soil erosion rate. The decline in soil thickness caused by erosion leads to local removal of soil on hillslopes. Soil eroded from the hilltops is redistributed across the landscape by soil transport and depositional processes (e.g., Pennock & Frick, 2001) and can ultimately leave fields via transport by water (e.g., Quine et al., 1994).

Although some sedimentation studies have assessed anthropogenic soil erosion over long timescales (e.g., Heathcote & Downing, 2012; Heathcote et al., 2013), most studies tend to integrate over timescales limited to a few decades or less (García-Ruiz et al., 2015; Montgomery, 2007b; Figure S1 in Supporting Information S1). Remote sensing (e.g., Thaler, Larsen, et al., 2021) and soil survey-based methods (Jelinski & Yoo, 2016) can provide information on the areal extent of degraded soil, but such methods cannot quantify the total thickness of soil that has been eroded since the initiation of farming or rates of historical soil erosion. Hence in major agricultural regions, historical erosion rates averaged over the period following the initiation of farming to the present day are unknown. The lack of robust estimates of long-term agricultural erosion rates impedes our ability to assess temporal trends in soil erosion and evaluate the degree which recent conservation efforts have reduced erosion rates below historical levels.

Rates of soil erosion have been estimated from sediment budget studies, where a mass balance approach is applied by assuming that the volume of sediment delivery is proportional to the volume of soil eroded upstream (De Vente et al., 2007). Agricultural soil erosion can increase river sediment loads and sediment accumulation rates. For example, sedimentation rates in North America have increased tenfold following the initiation of agriculture (Kemp et al., 2020). However, the ability to directly relate fluvial sediment yields to erosion rates at cultivated upland sites is complicated by internal basin dynamics, including sediment storage within fields, floodplains, water bodies, and internally drained basins, the latter which are common in postglacial landscapes with hummocky topography (Lai & Anders, 2018). In the Midwest, sediment budget studies have reached different conclusions regarding trends in agricultural soil erosion. In the Driftless Area of Wisconsin, late twentieth century decreases in alluvial sedimentation rates suggest agricultural erosion rates declined following implementation of conservation practices (Trimble, 1999). However, alluvial sedimentation rates in the Sangamon River valley in Illinois have been relatively constant since 1870, suggesting soil erosion rates may not have decreased in the decades following the initiation of soil conservation efforts (Grimley et al., 2017). Fluvial sediment yields in other watersheds in the region, such as the Minnesota River, primarily reflect stream bank or bluff erosion related to Pleistocene river dynamics and recent changes in discharge, and hence cannot be used to infer erosion rates on agricultural uplands (Belmont et al., 2011; Gran et al., 2009, 2013; Schottler et al., 2014). Further, sediment yield studies do not provide information on the total magnitude of soil that has been eroded from uplands since the initiation of agriculture, and such studies still often rely on model predictions to infer historical changes in agricultural erosion rates (e.g., Trimble & Lund, 1982).

The U.S. Department of Agriculture National Resources Inventory (USDA NRI; U.S. Department of Agriculture, 2018) provides a subdecadal assessment of soil erosion rates at specific sites throughout the U.S. based on climate, soil property, and land use data. Site characteristics are used as parameters for the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997) and the Wind Erosion Equation (Woodruff & Siddoway, 1965), which provide empirical estimates of soil loss by sheetwash and rill and wind erosion, respectively. A separate approach to assessing region-wide erosion, the Daily Erosion Project (DEP; Cruse et al., 2006; Gelder et al., 2018), uses the physically based Water Erosion Prediction Project (WEPP) model (Laflen & Flanagan, 2013), which integrates topography, precipitation, soil property, and crop data to provide daily estimates of the mass of soil eroded from hillslopes in Iowa, Nebraska, Minnesota, Wisconsin, and Kansas at the scale of ~90 km^2 watersheds. However, RUSLE and WEPP do not incorporate tillage or gully erosion in their model predictions, which can be important drivers of soil transport (Govers et al., 1996; S. Li et al., 2008; Öttl et al., 2021; Papiernik et al., 2009; J. Poesen, 2018; J. W. Poesen et al., 1996; Thaler, Larsen, et al., 2021; Valentin et al., 2005; Van Oost et al., 2006). NRI estimates of soil loss have been generated every 5 years from 1982 to 2017 and temporal trends suggest that erosion rates have generally been decreasing since 1982 (U.S. Department of Agriculture, 2018). Models used to assess changes in erosion rates for periods before and after the implementation of soil conservation practices in the U.S. predict large reductions in erosion (e.g., Trimble & Lund, 1982). However, the lack of measurements of upland soil erosion rates that span long timescales makes it difficult to empirically assess whether contemporary erosion rates are substantially lower than rates prior to the mid-twentieth century. Such measurements are required to determine whether erosion rates have declined in the period following the advent of soil conservation practices.

The magnitude and temporal trends in soil erosion in the U.S. inferred from sediment budget and soil loss modeling do not agree, which has led to the conclusion that contemporary rates of soil erosion are poorly constrained (Trimble & Crosson, 2000). Here, we take a different approach to assessing erosion and report decreases in soil thickness based on field measurements of the height of topographic escarpments generated by agricultural erosion (e.g., Kaiser, 1961; Papendick & Miller, 1977) at the boundary between native prairie remnants and agricultural fields at sites throughout the Midwestern U.S. We relate the measurements of the reduction in soil thickness to topographic curvature and use high-resolution topographic data to generate a new regional estimate of soil erosion rates in the Midwest that spans the time from the initiation of agriculture in the mid-1800s to the present day and compare our results against predictions from the NRI and DEP.

2. Study Area

The Midwest is an important agricultural region that produces most of the corn and soybeans in the U.S. (U.S. Department of Agriculture, 2017). Here, we define the Midwest as the region in the midcontinental U.S. that was primarily tallgrass prairie or savanna prior to cultivation, though other ecosystems such as hardwood forests were more common in the east, due to greater precipitation (Figures S2 and S3 in Supporting Information S1; Carnahan, 1977; Daly et al., 1997). We specifically define our study area as portions of the states of North Dakota, South Dakota, Minnesota, Nebraska, Kansas, Missouri, Illinois, Indiana, and the entire state of Iowa (Figure 1). The study area generally falls within the extent of Pleistocene glaciation, except for part of north-east Kansas and the Driftless Area along the Wisconsin–Iowa border. All areas we study have high-resolution, lidar-based topographic data. The tallgrass prairie ecosystem led to the development of organic-carbon-rich mollisol soils (Samson & Knopf, 1994). Due to the productive soils, the prairies were rapidly converted to agricultural fields within a few decades of the arrival of European–Americans (Smith, 1992, 1998). Today less than 0.1% of the prairie remains (Samson & Knopf, 1994). Although most of the land in the Midwest has been converted to agricultural fields, small native prairie remnants, which were spared from cultivation, are preserved throughout the landscape (Figure 1). Because the native prairies have not been anthropogenically altered, they preserve the presettlement topography; natural erosion in the prairies occurs at such low rates that the topography can be considered static over post-European settlement timescales. For example, erosion rates measured using meteoric ^{10}Be concentrations from a prairie and a nearby agricultural field in Minnesota indicate that the natural erosion rate of the prairie is 0.047 mm year^{-1} compared to an agricultural erosion rate of 3.09 mm year^{-1} in the field (Jelinski et al., 2019). Our field observations indicate that when prairie remnants are located upgradient from adjacent agricultural fields, an escarpment is commonly present at the prairie-field boundary because agriculturally accelerated erosion within the fields outpaces natural erosion in the prairies (Figure 2), and the development of such escarpments is predicted by numerical models that simulate soil transport by tillage (e.g., Follain et al., 2006; S. Li et al., 2009; Van Oost et al., 2000; Vieira & Dabney, 2009). Hence, we measured the height of the erosional escarpment to quantify the decline in soil thickness that has occurred at these points on the landscape from the time cultivation began (approximately 1850–1900 CE) up to the present day. We use the field measurements in combination with high-resolution topographic data and a mathematical model of lateral soil transport to make spatially explicit predictions of the historical decline in soil thickness for agricultural fields across the Midwest.

3. Methods

3.1. Topographic Surveys

We used a real-time kinematic global positioning system (RTK GPS) to conduct cm-scale accuracy topographic surveys across the prairie-field boundary at 20 sites throughout the Midwest (Figure 1). A minimum of 10 transects were surveyed at each site, and transect locations were selected to span the range of topographic curvature at each site. At each transect, the height of the erosional escarpment was determined by using linear regression to extrapolate the elevation of the prairie surface across the erosional escarpment and into the field (Figure 2). The elevation at the base of the escarpment was determined by fitting a linear regression to survey points in the field. The escarpment height, which is equivalent to the reduction in soil thickness caused by erosion, was calculated

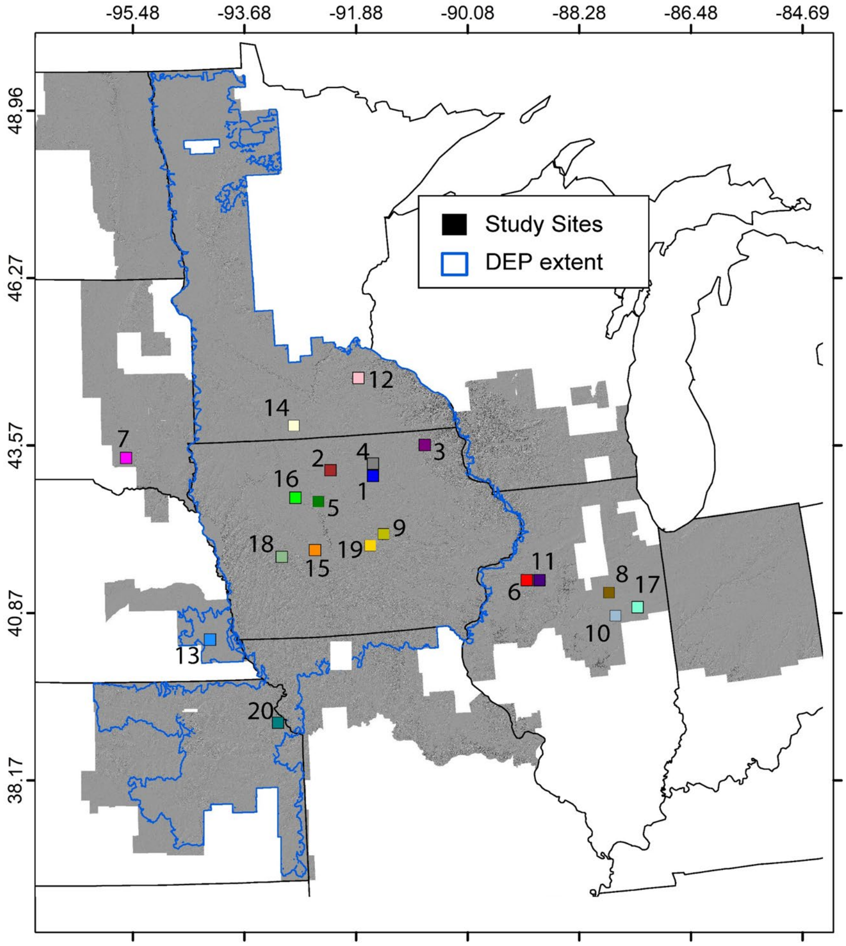

Figure 1. Location of the individual study sites (squares) within the Midwestern U.S. A region-wide decrease in soil thickness was predicted for areas with lidar topographic data, defined by the extent of the gray hillshade map. The blue outline shows the bounds of the Daily Erosion Project (DEP) data used in our study. The numbers correspond to each field site: 1, Willis; 2, Stinson; 3, Hayden; 4, Hoffman; 5, Kalsow; 6, Munson; 7, Steinauer; 8, Voight Pauper; 9, Kurtz; 10, Weston; 11, Greenlee; 12, McKnight; 13, Fricke; 14, Blue Gentian; 15, Judson; 16, Newell; 17, Loda; 18, Dinesen; 19, Harker; 20, Sheppard.

as the difference between the two regression lines at the base of the erosional escarpment. Use of the regression relationships accounts for the slope of the ground surface, resulting in more accurate determination of the reduction in soil thickness relative to simply comparing the elevation at the edge of the prairie versus the edge of the field, which would overestimate the change in soil thickness. In a few cases, the prairie and field slope in opposite directions, and rather than use linear regressions, the height of the escarpment was used to determine the change in soil thickness. Examples of escarpments, transects, and the inferred reduction in soil thickness are shown in Figure 2. At a small number of transects, deposition was observed and measured along the prairie-field boundary.

We estimated a soil erosion rate (Figure 3) by dividing the change in soil thickness by the time since the initiation of cultivation. Several of the prairies are pioneer cemeteries, and at these sites the date of the earliest gravestone was assumed to coincide with the initiation of cultivation. For the noncemetery sites, we assumed that cultivation began when the ownership of the land parcel was transferred from U.S. government to private individuals, based on records from the U.S. General Land Office Records (Bureau of Land Management, 2021). Dates of land transfer and hence the assumed initiation of cultivation range from 1846 to 1902. At 16 of the 20 study sites, the fields are still cultivated for row crop agriculture. The fields at the Loda, Judson, and Steinauer sites have been removed from row crop production within the last decade, but we do not know the exact year for each site. Therefore, we assumed that cultivated ceased in 2019 when we surveyed the fields, which leads to a conservative estimate of the erosion rate because the integration time is longer. The cessation of cultivation at the McKnight site occurred

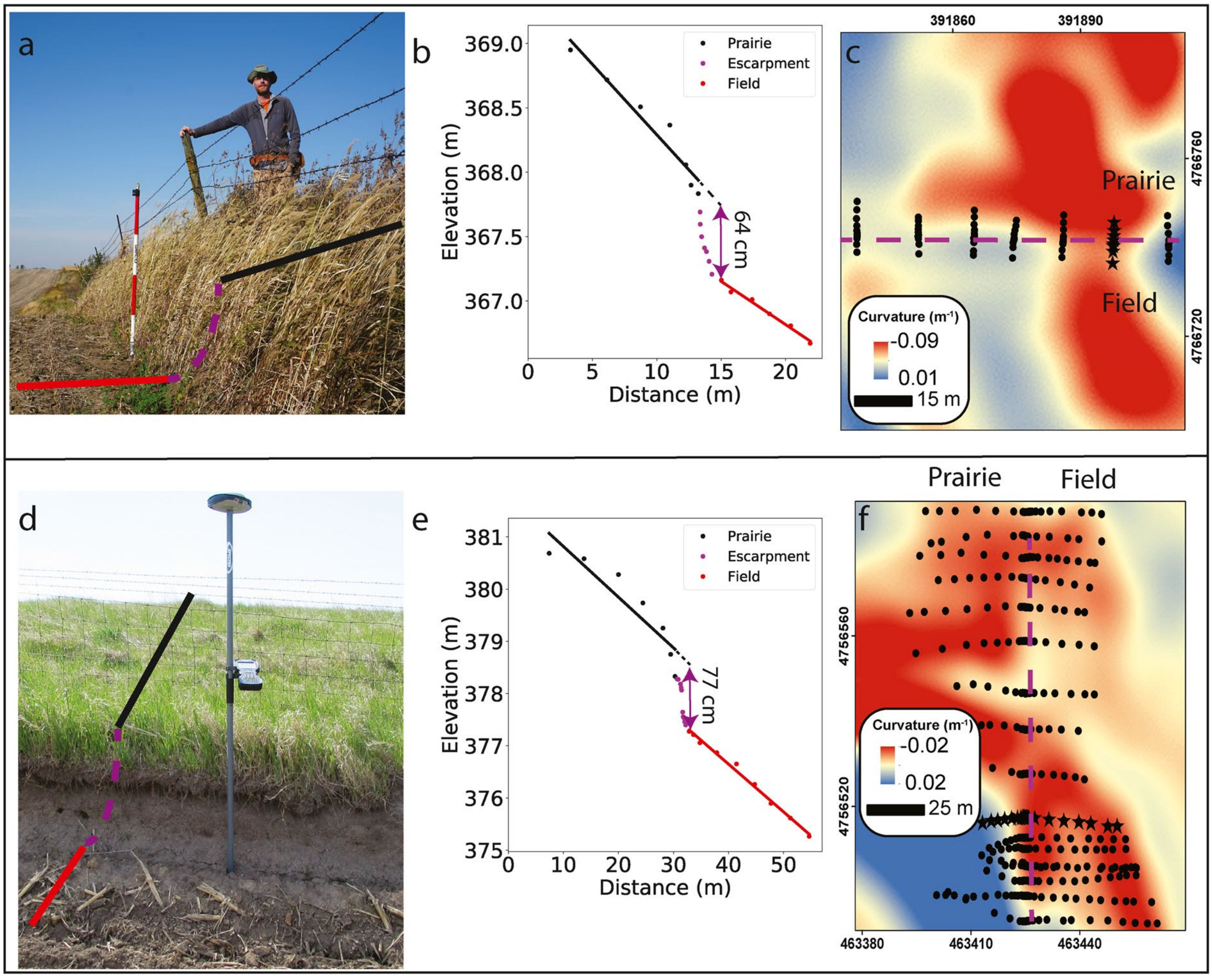

Figure 2. Examples of erosional escarpments and real-time kinematic global positioning system (RTK GPS) survey data analysis. (a) Photograph of an escarpment between the native prairie (right) and the adjacent agricultural field (left) at Stinson Prairie. (b) An example survey transect and calculated elevation offset. In this example, the offset and change in soil thickness is 64 cm. (c) Map of topographic curvature, where red pixels indicate convex topography, and blue values indicate concave topography. GPS transect lines are shown as black dots, and the black stars indicate the transect shown in (a) and (b). The boundary between the prairie and field is shown as a magenta dashed line. (d) Photograph of an escarpment between the native prairie (top) and the adjacent agricultural field (bottom) at Willis Prairie. (e) An example profile of a surveyed transect and estimated elevation offset. In this example, the offset and change in soil thickness is 77 cm. (f) Same as (d), but for the Willis site. In (b) and (e), the prairie survey points and estimated topographic gradient are shown as the black points and line, respectively; the escarpment is shown as magenta points, and the points in the field and estimated topographic gradient are shown in red.

earlier, in the late 1960s, leading to an integrated erosion period of ∼100 years. The measurements of the decline in soil thickness integrate over the time since cultivation began and allow us to assess an average agricultural erosion rate but do not permit detection of temporal changes in erosion rates during the postsettlement period.

3.2. Topographic Controls on Historical Erosion Rates

Lidar point cloud data from the U.S. Geological Survey (USGS) National Map (Gesch et al., 2009) were used to generate 0.5 m spatial resolution digital elevation models (DEMs) for each site. We used a high-pass Gaussian filter from the *Python* package *astropy* (Astropy Collaboration et al., 2018) to smooth the DEMs to 4 m resolution, which is the optimal spatial resolution to calculate curvature for fields in this region (Thaler, Larsen, et al., 2021). Because the Gaussian filter samples from a spatial averaging window, the smoothing has the potential to greatly change the elevation values near the excarpment between the prairie and the field. To avoid this, we masked out the field-prairie boundary before applying the filter. We then calculated topographic curvature for each smoothed DEM and extracted the curvature values for each transect location.

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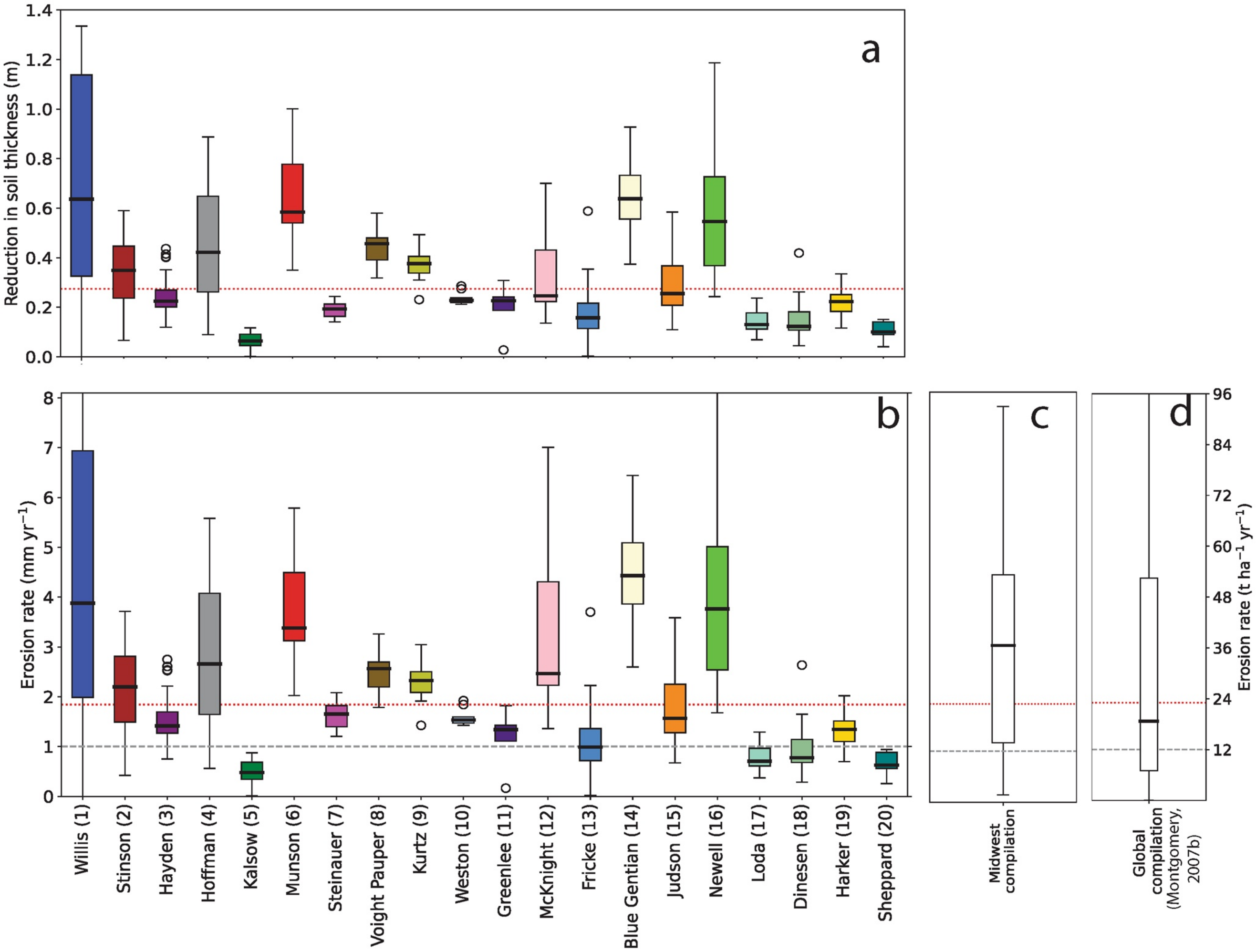

Figure 3. Boxplots of the decline in soil thickness and estimated erosion rates at each study site. (a) Boxplot of the measured decline in soil thickness (m) for each of transect at each of the 20 sites. The median decline in soil thickness for all sites (0.3 m) is shown as the red dotted line. (b) Boxplot of erosion rates determined for each site. The U.S. Department of Agriculture (USDA) soil loss tolerance (*T*) value is the same for all sites (1 mm year^{-1}) and is shown as the gray dashed horizontal line. The red dotted line indicates the median value from all sites (1.9 mm year^{-1}). Fifteen of the 20 sites have median erosion rates greater than the *T* value. Erosion rates were converted to a mass flux (t ha^{-1} year^{-1}) by assuming a uniform bulk density of 1,200 kg m^{-3}. The numbers for each site correspond to the numbers in Figure 1. (c) Boxplot with compilation of previously published soil erosion rates within the study region. The red dotted line indicates the median value from all the prairie sites. (d) Boxplot with compilation of previously published global agricultural erosion rates (Montgomery, 2007b). The median global erosion rate in agricultural landscapes is 1.54 mm year^{-1}. For each plot, the box spans the interquartile range; the black line is the median, and the bottom and top whiskers represent 5th and 95th percentiles, respectively. Outliers are shown as open circles. The colors of the boxes in (a) and (b) match those in Figures 1 and 4.

We fit a linear regression between the measured change in soil thickness and topographic curvature (Figure 4a) using data from all 20 study sites to derive a relationship that we used to predict changes in soil thickness throughout cultivated lands in the Midwest. We were unable to determine relationships between the change in soil thickness and curvature for each field site individually because many of the sites have a very limited range of curvature values, often with values only between −0.001 and 0 m^{-1} (Figure 4a), which precluded regression analysis. We used the regression relationship to estimate region-wide changes in soil thickness using topographic curvature values from 390,407 km^2 of lidar-derived DEM data. We estimated the uncertainty of the region-wide prediction using a Monte Carlo simulation which accounted for uncertainties in the slope and intercept of our empirical relationship between the change in soil thickness and topographic curvature. We randomly selected slope and intercept values from the compiled field sites dataset of soil thickness and topographic curvature 1,000 times and used the resulting 1,000 regression equations to estimate the change in soil thickness using curvature values from each cell in the full curvature dataset. The slope values were drawn from a normal distribution with the standard deviation (S.D.) defined by the 68th percentile confidence interval from our empirical fits (Figure 4a).

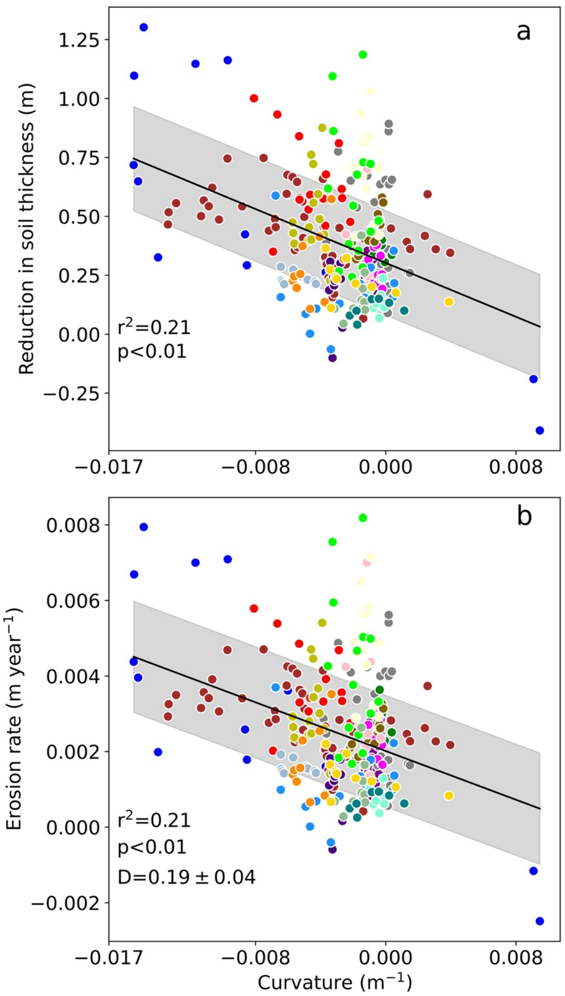

Figure 4. (a) Measurements of the reduction in soil thickness versus topographic curvature for each of the 304 transects at the 20 sites. The points are colored by site location, which matches colors in Figures 1 and 3. The gray shaded area represents the 68% prediction interval, which is ±0.22 m. The equation of the regression line (mean ± 68% interval) for the full data set is $y = (-28.9 \pm 6.3)x + (0.24 \pm 0.22)$. (b) Erosion rate versus topographic curvature for each of the transects. The gray shaded area represents the 68% prediction interval, which is ±0.0015 m year^{-1}. The equation of the regression line for the full data set is $y = (0.19 \pm 0.04)x + (0.002 \pm 0.0015)$. The diffusion coefficient (D) calculated from the full data set is equivalent to the slope of the regression line, 0.19 ± 0.04 m^2 year^{-1}.

The y-intercept values were sampled from a normal distribution with the S.D. defined by the 68th percentile prediction intervals defined by the empirical measurements (Figure 4a).

3.3. Calibration of a Topographic Diffusion Coefficient

Our field measurements of the reduction in soil thickness integrate the combined influence of all erosion processes, but the greater reduction in soil thickness and erosion rates on more convex topography indicates a diffusive soil transport mechanism is the primary driver of erosion. Tillage erosion is the movement of soil by repeated tillage operations (Van Oost et al., 2006), where soil is preferentially removed from topographic convexities and deposited in topographic concavities, which causes landscapes to evolve via topographic diffusion. We used our estimates of the time-integrated soil erosion rate and measurements of topographic curvature to estimate a region-wide coefficient of topographic diffusion. The diffusion-like evolution of topography can be modeled as

$$dz/dt = D\nabla^2 z \tag{1}$$

where dz/dt is erosion rate averaged since cultivation began [L t^{-1}], D is a diffusion coefficient [L^2 t^{-1}] that integrates factors that influence soil movement, such as tillage direction, tillage depth, and soil physical characteristics, and $\nabla^2 z$ is the Laplacian operator of z, or topographic curvature [L^{-1}], a measure of landscape convexity. By rearranging Equation 1, D can be estimated by calculating the slope of the regression line fit to the rate of soil thickness change calculated from the RTK GPS surveys (dz/dt) and land transfer records, and topographic curvature ($\nabla^2 z$) data (Figure 4b). D and its ±1 S.D. uncertainty were calculated from the slope of the regression line through the erosion rate and curvature data from all sites (Figure 4b). We also performed the same Monte Carlo analysis for regression between erosion rate and curvature values (Figure 4b) and assessed the uncertainty in our estimate of D using the 68% confidence interval of the slope value. The D value determined using this approach is a time-averaged value, as soil transport rates likely changed when non-mechanized agriculture was replaced by mechanized farming practices (Kwang et al., 2022).

Due to the low erosion rates in the prairies, there is virtually no downslope sediment flux from the prairies into the adjacent fields. The lack of upslope sediment supply to the field causes an additional elevation offset, as soil is moved downslope in the field but not replenished from upslope sources, a process which does not occur in areas without such a boundary. We evaluated the height of the escarpment that would be generated by such a no-flux boundary using an analytical model for hillslope evolution by diffusion described in Figures S4–11 in Supporting Information S1 and assess the influence of the no-flux boundary on our results.

3.4. Regional Estimates of the Historical Reduction in Soil Thickness

We calculated region-wide topographic curvature from lidar-derived topographic data at the same 4 m grid scale we used for the individual sites (Figure 1) and used the curvature data to empirically predict region-wide estimates of the reduction in soil thickness. The 4 m raster was first clipped to include only agricultural croplands using the Herbaceous Agriculture raster from the USGS Gap Analysis data set (Jennings, 2000). Waterways were removed from the DEM using a 50 m buffer from flowline centers identified by the National Hydrography

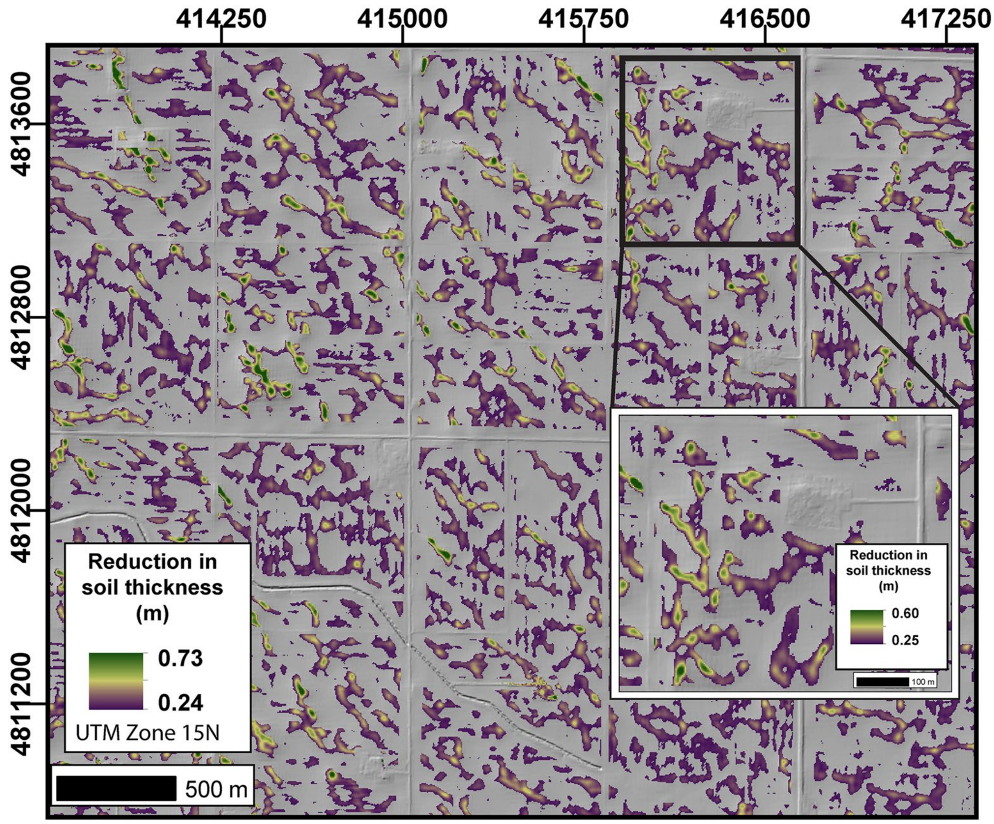

Figure 5. Example of predictions of the decline in soil thickness from 16 km^2 of convex topography near Lakota, Iowa. Purple pixels indicate areas with lower reductions in soil thickness, while areas with a greater estimated reduction in soil thickness are shown green pixels. The total estimated mass of eroded soil in the full example extent is 98,784 metric tons. The inset demonstrates the removal of areas with buildings, roads, and fence lines from the analysis. Within the inset, we estimate 3,688 metric tons of eroded soil on 0.63 km^2 of convex topography.

Dataset (Horizon Systems Corporation, 2007), transit lines (roads, railways, etc.) were removed using a 30 m buffer from transit line centers within the National Transportation Dataset (U.S. Geological Survey, 2014), and property boundaries, which contain fence rows that can lead to anomalous curvature values, were removed using the Agricultural Conservation Planning Framework data set (Tomer et al., 2017). The buffer sizes were chosen to remove stream banks, ditches, and other infrastructure along transit lines that have curvature values which are not representative of cultivated fields.

For each pixel in the curvature grid, we predicted the total change in soil thickness and its uncertainty since the initiation of cultivation. The change in soil thickness was converted to a mass of eroded soil using an assumed uniform soil bulk density of 1,200 kg m^{-3}, which is the median bulk density value for samples collected by the USDA Rapid Carbon Assessment within our study area (Wills et al., 2014). Because our surveys indicate the decline in soil thickness is the greatest on convex hillslopes, we only made predictions for the areas of fields with convex topography ($\nabla^2 z < 0$), resulting in an area of 165,033 km^2 where we calculated the total mass of eroded soil. The total mass of soil removed from convex hillslopes was converted to an erosion rate by dividing by the mean time of cultivation for all of our study sites, which is 155 years. An example raster showing predictions of the decline in soil thickness for an area in north-central Iowa is shown in Figure 5.

3.5. Comparison Against Other Erosion Rate Estimates

We determined the annual soil loss (mm year^{-1}) via water erosion estimated by the 2017 NRI soil erosion assessment (U.S. Department of Agriculture, 2018). The NRI erosion estimates are derived using RUSLE (Renard et al., 1997) at target cells, which contain a surveyed field site. Wind erosion predictions from the NRI were not available to us, but with the exception of the Red River valley region in Minnesota and North Dakota, water erosion is predicted to be a more dominant erosion mechanism than wind in our study area (U.S. Department of Agriculture, 2000). The NRI methodology interpolates soil loss estimates to 2.5 km^2 spatial resolution for areas within 80 km of target cells. We determined the average annual hillslope soil loss rate predicted by the DEP from 2007 to 2020 by summing the total mass of soil transported to the base of hillslopes for each year and dividing by the number of years of predictions (13 years). Estimates of soil loss from the NRI and DEP have units of annual mass flux [M L^{-2} t^{-1}], and these values were converted to an erosion rate [L t^{-1}] by assuming a uniform bulk density of 1,200 kg m^{-3}. We then generated histograms and used a kernel density estimator to plot the probability distribution of the erosion rates derived from the NRI, the DEP, the rates calculated from each survey transect, and the rates estimated from our regional scaling. In addition to estimating erosion rates from the full extent of our regional analysis, the NRI and our regional scaling results were clipped to the extent of the DEP data, which has the smallest spatial extent of the three data sets, so that the same areas are compared.

To contextualize the soil erosion rates calculated from our survey data and the region-wide predictions, we compiled previously published soil erosion rates for croplands within the Midwestern U.S. We further place the erosion rates we measure within a global context by comparing erosion rates for each field site against a compilation of global agricultural erosion rate data (Montgomery, 2007b).

4. Results

The median reduction in soil thickness at the 20 field sites ranges from 0.004 to 0.69 m (Figure 3a). The median time-integrated erosion rates calculated from the changes in soil thickness range from 0.002 to 4.3 mm $year^{-1}$, with a median value of 1.9 mm $year^{-1}$ for results across all 20 sites (Figure 3b). The greatest magnitudes of soil thickness change, and hence the greatest erosion rates, were measured in areas with the most convex topography ($\nabla^2 z < 0$; Figure 4a). At eight transects in topographic concavities, the elevation of the field is higher than the elevation of the prairie due to soil deposition, and these transects are indicated by negative changes in soil thickness and erosion rate values (Figures 4a and 4b). The historical change in soil thickness measured from the escarpment heights is linearly correlated with topographic curvature, with a coefficient of determination (R^2) of 0.21 and mean ± 1 S.D. slope and intercept values of −28.9 ± 6.3 and 0.24 ± 0.22 m, respectively. Similarly, there is a linear relationship between erosion rate and topographic curvature (Figure 4b), with a predicted D value of 0.19 ± 0.04 m^2 $year^{-1}$.

Since the initiation of farming, we estimate the total mass of soil eroded from convex topography to be $57.6 \times 10^9 \pm 37.8 \times 10^9$ metric tons across our study area. For the 165,033 km^2 of convex topography, the median historical averaged erosion rate equates to 22.5 ± 7.2 metric tons ha^{-1} $year^{-1}$ (1.8 ± 1.2 mm $year^{-1}$). For the area of convex topography within the extent of the DEP data (105,519 km^2), our scaling analysis predicts a total of $36.8 \times 10^9 \pm 13.2 \times 10^9$ metric tons of soil has been eroded, equating to a median erosion rate of 14.3 ± 9.2 metric tons ha^{-1} $year^{-1}$ (1.2 ± 0.8 mm $year^{-1}$; Figure 6). The median rate of soil loss estimated from the NRI assessment, within the full extent of our study area is 7.2 ± 4.8 metric tons ha^{-1} $year^{-1}$ (0.6 ± 0.4 mm $year^{-1}$), and the median rate estimated by the NRI within the extent of the DEP predictions is 6.0 ± 4.8 metric tons ha^{-1} $year^{-1}$ (0.5 ± 0.4 mm $year^{-1}$; Figure 6). The median rate estimated by the DEP is 2.4 ± 6.0 metric tons ha^{-1} $year^{-1}$ (0.2 ± 0.5 mm $year^{-1}$; Figure 6).

5. Discussion

5.1. Soil Erosion Rates in the Midwestern U.S.

Conversion of land from native tallgrass prairie to cultivation-based agriculture has caused soil thickness to decline by decimeters in the Midwestern U.S. The historical erosion rates documented by our surveys average over about 150 years and are consistent with previously measured soil erosion rates in the Midwest, which range from 0.14 to 7.7 mm $year^{-1}$ (Figure 3c). However, the previously documented erosion rates typically are based on only a few decades of measurement during the mid-twentieth century (Figure S1 in Supporting Information S1). Although our results cannot be used to assess whether soil erosion rates have increased or decreased over the last

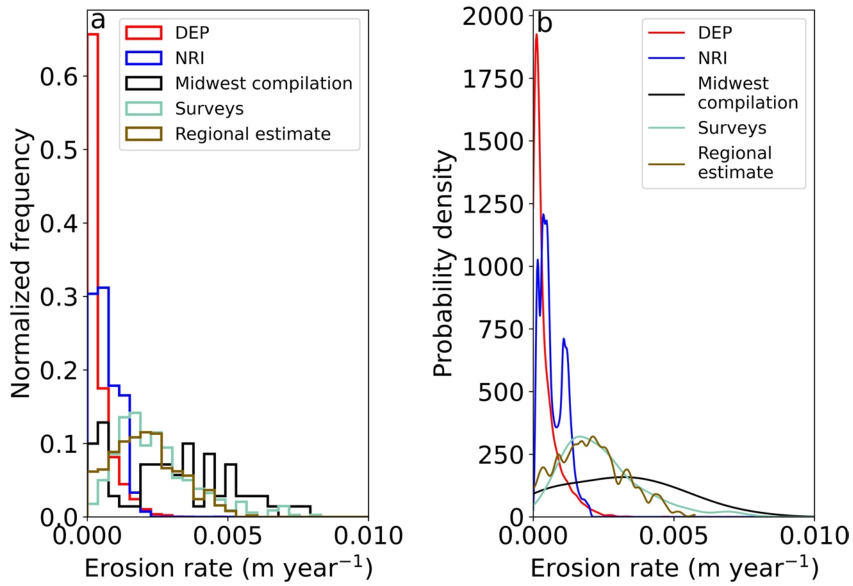

Figure 6. (a) Histograms indicating the distribution of erosion rates within the extent of the Daily Erosion Project (DEP) analysis (Figure 1) estimated by the DEP, indicated by the solid red line, the USDA National Resources Inventory (NRI), shown as a blue line, erosion rates from previous studies in the Midwest are shown as a black line, rates calculated from the individual 304 surveyed transects collected from the 20 field locations in this study are shown as the teal line, and regional scale historical erosion rate estimates calculated in this study are shown as the brown line. (b) Kernel density estimates of values shown in (a). Estimates of regional historical erosion rates and NRI estimates within the full extent of our study area are shown in Figures S16 and S17 in Supporting Information S1.

150 years, the similarity between our results and the twentieth century, decadal-averaged erosion rates (Figure 3c) suggest that average erosion rates in the Midwestern landscape have been high for the entire period spanning the initiation of farming to the present day.

To set a goal for reduction of soil degradation, the USDA has assigned a soil loss tolerance (T) value to all mapped soil units. The T value is defined as the "maximum rate of annual soil loss that will permit crop productivity to be sustained economically and indefinitely" (U.S. Department of Agriculture, 2018). T values are based on multiple characteristics including soil physical properties and assumptions regarding soil formation rates (Skidmore, 1982). In the U.S., T values range from 2.2 to 11.2 metric tons ha^{-1} year^{-1} (U.S. Department of Agriculture, 2018), which is equivalent to 0.4–1 mm year^{-1}, assuming a soil bulk density of 1,200 kg m^{-3}. The T value for the soils at all our study sites is equivalent to 1 mm year^{-1} (Figure 3), and it has been argued that such values are too high to adequately reduce soil loss to a sustainable level by balancing soil erosion and formation (Johnson, 1987; L. Li et al., 2009; Montgomery, 2007b). Our findings support those arguments; the median historical erosion rate exceeds the T value at 15 of our 20 field sites, indicating that soil erosion at these sites has outpaced even the most erosion-permissive soil conservation target set by the USDA for more than a century.

The five sites where our measured soil erosion rates are lower than T values are Kalsow, Loda, Dinesen, Fricke, and Sheppard. The Kalsow site has the second flattest topography in our data set, with a median topographic slope of 0.008 m m^{-1} calculated from the survey data, which might explain the low erosion rates we measured there. However, the other four sites with erosion rates lower than the T value have median topographic slopes of 0.001, 0.03, 0.01, and 0.02 m m^{-1}, respectively, which are greater than values at some sites where soil erosion rates outpace the T value, indicating that topography alone does not explain the relatively low erosion rates at the sites. Nor does soil parent material explain the lower erosion rates at some sites; the distribution of Quaternary deposits (Soller et al., 2009) indicates soils at the Dinesen and Sheppard sites formed from loess, whereas the soil parent material at the Kalsow, Harker, and Loda sites is glacial till. In the absence of clear topographic or parent material influences, it is possible that differences in historical agricultural practices, such as the frequency of tilling or the type of implements used for tilling, may contribute to differences in historical soil erosion rates across the sites. However, data on the history of farming practices at each site are not available to test that hypothesis.

5.2. Soil Redistribution Processes

The soil erosion we measure at each site is the sum of soil removal caused by all erosion processes, including rain splash, overland flow, biogenic soil creep, wind, and tillage. Our measurements cannot determine the relative importance of each mechanism. However, studies that have assessed the relative influence of tillage and water erosion demonstrate that both processes remove soil from convex topography, but that tillage tends to dominate, especially on the most convex parts of the landscape (e.g., Govers et al., 1996; Papiernik et al., 2009). The highest erosion rates we measured are on the most convex hilltops (Figure 4). Hence, we interpret the correspondence between topographic curvature and our measured erosion rates to indicate diffusive processes primarily reduces soil thickness on convex topography, particularly since convex ridgetop sites that we surveyed have little upslope accumulation area to generate overland flow but have lost decimeters of soil. Further, the D value calibrated from our measurements of erosion rate and topographic curvature (0.19 ± 0.04 m^2 year^{-1}; Figure 4b) is comparable to previously measured diffusion coefficients for tillage erosion, which range from 0.03 to 0.52 m^2 year^{-1} (Van Oost et al., 2006), and indicates that tillage erosion plays a large role in redistributing soil from convex hillslopes to topographic convexities. These results provide further evidence that tillage erosion has been a primary driver of soil degradation in the Midwest (De Alba et al., 2004; S. Li et al., 2008; Thaler, Larsen, et al., 2021) and elsewhere (Montgomery, 2007a, 2007b).

We expect that the relative importance of water erosion increases downslope, as flow accumulation increases (e.g., Bryan, 2000; S. Li et al., 2007; Van Oost et al., 2005). Organic-carbon-rich A-horizon soils have been removed from a large proportion of agricultural fields in the Midwest, and about one third of the area with A-horizon removal has concave topography, suggesting that water erosion plays a significant role in removing soil from concave slopes (Thaler, Larsen, et al., 2021). We measured reductions in soil thickness for most of the survey transects in areas with concave topography, and water erosion may have been important in those locations.

The fate of soil eroded from convex topography cannot be assessed using the methodology presented in our study; however, both ^{137}Cs budget and modeling studies indicate that the combination of tillage and water erosion on convex slopes leads to redistribution of soil to concave landscape positions (Govers et al., 1996; Kwang et al., 2022; Papiernik et al., 2009; Quine et al., 1994; Van Oost et al., 2000, 2005). The soil that is deposited in topographic concavities can be exported to drainage networks, but the rates of deposition have been shown to be greater than rates of soil export via water erosion (Pennock & De Jong, 1987; Van Oost et al., 2000), leading to an overall increase in soil thickness in concavities within agricultural fields. Although we infer tillage is an important soil erosion processes, water and tillage erosion both degrade soils on convex topography. Given the longer transport distances for soil particles advected by water versus moved diffusively by tillage, water erosion is more likely to transport soil from fields and impact downstream water quality. Hence, conservation efforts designed to limit soil transport by both water and tillage erosion are valuable for reducing soil degradation and limiting offsite impacts to water resources.

5.3. Influence of Boundary Conditions and Topographic Diffusion on Erosion Rate Estimates

The height of the escarpment at the boundary between each field and prairie is influenced by two factors, the divergence of the soil flux in the direction parallel the boundary and the lack of soil flux across the boundary from the prairie to the field. The magnitude of boundary-parallel soil flux results in a reduction in the elevation of convex topography and deposition in areas with concave topography. However, in cases where the prairie slopes toward the field, the lack of soil flux perpendicular to the boundary results in a greater decline in soil thickness adjacent to the boundary than elsewhere within the field (Follain et al., 2006; Vieira & Dabney, 2009). If the reduction in soil thickness caused by the no-flux boundary is a large fraction of the total reduction in elevation or soil thickness, then our surveys may overestimate the decline in soil thickness and erosion rates relative to other locations within each field that have the same topography. We developed an analytical landscape evolution model that simulates topographic evolution via topographic diffusion, described in the Supporting Information S1, to separately quantify the contributions of boundary-parallel and boundary-perpendicular soil flux to the change in elevation that occurs near the prairie-field boundary.

The analytical model predicts that the change in elevation caused by the lack of soil flux across the boundary is a function of the initial, preagricultural hillslope angle. We use survey points in the prairies to estimate the initial slope at each transect and use the slope values to predict the magnitude of the elevation change caused by the no-flux boundary using a 1-D analytical model (Figure S12 in Supporting Information S1). We assume that the slope of the prairie is representative of the preagricultural slope in the adjacent field.

For hillslopes with relief and slope lengths representative of our field sites and the median prairie slope value (0.04 m m^{-1}), our 1-D analytical model predicts that the escarpment height caused by the no-flux boundary at individual cross sections is 25.5 cm, which is large relative to many of our measurements. However, the predicted elevation change caused by the no-flux boundary exceeds the surveyed elevation change at 38% of our surveyed cross sections (Figure S13 in Supporting Information S1). Hence, our 1-D analytical model overestimates the contribution of the no-flux boundary to total escarpment height; the values need to be reduced uniformly by 90% for all the predictions to be lower than the elevation changes we measured.

It is unclear why the analytical model overestimates the elevation change caused by the no-flux boundary, relative to our measurements. However, there are several lines of evidence that further suggest the no-flux boundary does not have a large influence on our erosion rate estimates. Tillage typically occurs in a direction that is parallel to the prairie-field boundary (Figure S14 in Supporting Information S1). Tracer studies have shown that tillage primarily moves soil in the same direction as tillage, such that soil flux in the direction perpendicular to tillage, or perpendicular to the prairie-field boundary, is 25% lower than the boundary-parallel soil flux (De Alba et al., 2001; Lindstrom et al., 1990). The anisotropy in soil flux caused by tillage is not accounted for in our model but doing so would presumably reduce the predicted elevation changes by 25%.

A value of D has been independently determined for three of the field sites, Stinson, Hoffman, and Willis using decreases in soil thickness inferred from satellite imagery and the depth dependence of soil spectral reflectance in the adjacent prairies (Kwang et al., 2022). The mean D value for the three sites of 0.25 m^2 $year^{-1}$ is of similar magnitude, though slightly higher than the value we have inferred from the topographic surveys and curvature data. The D values estimated by Kwang et al. (2022) are based on pixels throughout each field and hence are not influenced by the no-flux boundary. The similarity in D values indicates that the erosion rates we measure near the boundary are of similar magnitude to erosion rates that are occurring throughout each field, and hence that our survey-based erosion rates are not overestimates. The erosion rates we measure are also of similar order to prior measurements in the Midwest, though the median value we measure is about one third lower than the median from our compilation of prior measurements (Figure 3), which, again, suggests that the erosion rates we measure are not being greatly increased by the no-flux boundary.

Finally, if the no-flux boundary generates additional reductions in soil thickness along the boundary, then soils should be the most degraded at the boundary and become less degraded at increasing distance from the boundary. However, analysis of soil spectral properties related to the degree of soil degradation (Thaler et al., 2019) from soil topographic transects at Stinson, Hoffman, and Willis indicates that there is no pattern of increased soil degradation toward the boundary (Figure S15 in Supporting Information S1).

The topography of landscapes affected by diffusive soil transport processes becomes smoother over time. Landscape evolution modeling based on idealized sinusoidal topography suggests that landscape convexity has decreased by ~7% since cultivation began, assuming hillslope lengths and wavelengths that are representative of our field sites. Since our calculation of D relies on the relationship between erosion rate and present-day topographic curvature, the predicted change in convexity suggests that our D value is a ~4% overestimation (Supporting Information S1). The uncertainty in D caused by topographic change is small relative to the likely magnitude D has changed due to the conversion of prairies to farms. The D value we calculate is still 1–3 orders of magnitude greater than values measured in nonagricultural settings (Fernandes & Dietrich, 1997), which implies that agriculture has increased soil transport and erosion rates in the Midwest by orders of magnitude.

5.4. Comparison of Region-Wide Erosion Predictions

Soil loss predictions from RUSLE and WEPP are for the part of the landscape between where runoff initiates and where erosion by concentrated flow dominates (Gelder et al., 2018), whereas our predictions are for the part of the landscape with convex topography. The different model frameworks complicate direct comparison of model results, but all three approaches focus on upland parts of the landscape and exclude depositional areas. Inasmuch as the values can be directly compared, the median soil loss rate predicted by the NRI is a factor of 3 lower than our estimates, and the median soil loss rate predicted by the DEP is a factor of 8 lower. The lower rates predicted by the NRI and the DEP relative to the rates estimated by our analysis might suggest that modern erosion rates are lower than historical values. Indeed, within the Midwestern U.S., subdecadal scale estimates of soil erosion from the NRI indicate that soil erosion rates decreased by 34% from 1982 to 2015 (U.S. Department of Agriculture, 2018). However, sedimentation data from lakes in Iowa indicate that most of the sediment has accumulated since 1950, which is temporally associated with the onset of agricultural intensification, rather than the initial land conversion to agriculture (Heathcote & Downing, 2012; Heathcote et al., 2013). The sedimentation rate data have led to the conclusion that conservation programs have not reduced downstream sediment delivery (Heathcote et al., 2013). Our regional estimates of soil erosion are based on the sum of all erosion processes (water, wind, tillage, etc.) captured by our field measurements. Whereas the NRI or the DEP predictions may be valid for assessing erosion by water, neither model includes tillage in their predictions of erosion, even though tillage is an important soil transport process in the Midwest (Papiernik et al., 2009; Thaler, Larsen, et al., 2021). Hence, rather than interpreting the difference between the historically averaged soil erosion rates we measure and modeled contemporary soil loss rates as a decline in erosion over time, we suggest the NRI and DEP may be underpredicting the current rates and magnitudes of soil loss in the Midwest because they do not incorporate the effects of tillage. Therefore, there is a need to incorporate existing tillage erosion models (De Alba, 2001; Kirkby et al., 2008; S. Li et al., 2008; Van Oost et al., 2005) within the models used to predict soil loss in the U.S. The NRI framework also currently does not include the ability to spatially resolve all relevant soil transport processes that lead to soil loss from convex hilltops, deposition in topographic lows, and transport of soil from fields, which hinders the ability to accurately predict contemporary rates of soil erosion, redistribution, and export from fields in the U.S.

6. Summary and Implications

When compared against *T* values and available long-term rates, our findings indicate that soil erosion rates in the Midwest are occurring at unsustainable levels and there is not a clear indication that the rates have declined since soil conservation practices and policies were implemented in the wake of the Dust Bowl of the 1930s. The erosion rates we estimate in the Midwest are consistent with rates in other agricultural regions across the globe (1.54 ± 0.3 mm year^{-1}; Montgomery, 2007b; Figure 3d), indicating that high rates of soil erosion are not unique to our study region. These similarities suggest that efforts must be taken at a global scale to reduce agriculturally induced soil erosion (Montgomery, 2017; Handelsman, 2021). Although there are political, social, and economic barriers to their implementation (Amundson & Biardeau, 2018; Schlesinger & Amundson, 2019), methods such as no-till farming (Montgomery, 2007b) and soil regenerative practices (Loisel et al., 2019; Montgomery, 2017) have the ability to reduce erosion rates. Incentivizing such practices (e.g., National Science and Technology Council, 2016) will likely be required to reduce soil erosion rates in the Midwest to levels that can sustain soil productivity, ecosystem services, and long-term prosperity (Amundson et al., 2015).

Data Availability Statement

We have archived the topographic survey data from each of the 20 sites, shapefiles indicating the boundary of the prairie and field sites, digital elevation models for each of the sites, rasters containing values for the mean, minimum, and maximum volume of soil lost for each county in the study area, and the compilation of published soil erosion rates measured within the study area. The data are available at https://doi.org/10.7275/76w5-1z60 (Thaler, Kwang, et al., 2021).

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