Pre-agricultural Soil Erosion Rates in the Midwestern U.S.

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Pre-agricultural Soil Erosion Rates in the Midwestern U.S.

A Thesis Presented

by

CAROLINE LAUTH QUARRIER

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2022

Department of Geosciences
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ABSTRACT

PRE-AGRICULTURAL SOIL EROSION RATES IN THE MIDWESTERN U.S.

MAY 2022

CAROLINE LAUTH QUARRIER, B.A. CARLETON COLLEGE
M.S. UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Isaac J. Larsen

Soil erosion undermines agricultural productivity, limiting the lifespan of civilizations. For agriculture to be sustainable, soil erosion rates must be low enough to maintain fertile soil, as was present in many agricultural landscapes prior to the initiation of farming. However, there have been few measurements of long-term pre-agricultural erosion rates in major agricultural landscapes. We quantified geological erosion rates in the Midwestern U.S., one of the world’s most productive agricultural areas. We sampled soil profiles from 14 native prairies and measured concentrations of the cosmogenic nuclide $^{10}$Be and chemically immobile elements to calculate physical erosion rates. We used the erosion rates and measurements of topographic curvature to estimate a pre-agricultural topographic diffusion coefficient. We find pre-agricultural erosion rates of 0.0001–0.1 mm yr$^{-1}$ and a site-averaged diffusion coefficient of 0.005 m$^2$ yr$^{-1}$. The pre-agricultural erosion rates and diffusion coefficient we measured are both orders of magnitude lower than anthropogenic values previously measured in adjacent agricultural fields. The pre-agricultural erosion rates are one to four orders of magnitude lower than the 1 mm yr$^{-1}$ soil loss tolerance value assigned to these locations by the U.S. Department of Agriculture. Hence, as currently defined, tolerable soil loss will lead to unsustainable
erosion of Midwestern soils. However, quantifying natural erosion rates via cosmogenic nuclides provides a means for more robustly defining rates of tolerable soil loss and developing management guidelines that promote soil sustainability.
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CHAPTER 1

PRE-AGRICULTURAL SOIL EROSION RATES IN THE MIDWESTERN U.S.

Introduction

The advent of agriculture was integral to the development of complex civilizations, but resultant soil erosion repeatedly contributed to societal decline (Montgomery, 2007a). The cost of soil erosion in the U.S. due to diminished agricultural productivity and off-site environmental degradation is estimated to be $40 billion annually (Pimentel et al., 1995). Erosion poses a challenge to global food security, which will be exacerbated by population growth and climate change (Amundson et al., 2015). Furthermore, soils contain about three times as much carbon as the atmosphere, thus quantifying erosion rates is essential for understanding the role soils play in the carbon cycle and their potential for mitigating climate change (Doetterl et al., 2016).

The long-term viability of agriculture depends on the existence of fertile soil, which can only be maintained by reducing agricultural erosion rates to levels that match natural rates of erosion and soil formation (Montgomery, 2007b). However, agricultural practices erode soil at rates 10 to more than 100 times greater than geological rates (Montgomery, 2007b; Nearing et al., 2017). Soil conservation efforts in the wake of the Dust Bowl led the U.S. Department of Agriculture to develop soil loss tolerance (T) values for U.S. croplands, which delimit maximum erosion rates that can sustain agricultural productivity indefinitely (Smith, 1941). However, the rates at which soil formed from parent materials could only be speculated during the early 20th century, and the efficacy of T values in sustaining soil has been subsequently been questioned (e.g., Johnson, 1987; Li et al., 2009; Shertz and Nearing, 2006).
Cosmogenic nuclides, such as $^{10}$Be, are now routinely used for measuring long-term denudation rates and soil production rates (e.g., Granger and Riebe, 2013). $^{10}$Be concentrations have been compared against contemporary sediment yield or soil erosion measurements to assess increases in soil erosion due to agriculture (Thorson Brown et al., 1998; Vanacker et al., 2007; Ruesser et al., 2015; Evans et al., 2019). However, most $^{10}$Be-based soil production rates compiled for comparison against agricultural erosion rates are from hilly or mountainous landscapes where cultivated agriculture is uncommon (Montgomery, 2007b). Except for a few recent studies focused on individual fields in Germany (Calitri et al., 2019), Minnesota, U.S. (Jelinski et al., 2019) and Poland (Loba et al., 2021), there is little quantitative data regarding rates of geologic erosion where soils have formed from Pleistocene loess and glacial deposits, which are the primary soil parent materials in many of Earth’s major agricultural regions.

Here we use in situ-produced $^{10}$Be concentrations and geochemical mass balance to quantify physical erosion rates averaged over millennial timescales at 14 native prairies in the Midwestern U.S. We calculate a pre-agricultural topographic diffusion coefficient from the erosion rates and site curvature. We compare the pre-agricultural erosion rates and diffusion coefficient against agricultural those previously measured in adjacent agricultural fields and assess whether T values for each site are adequate for sustaining soils.

**Study Site**

The Midwestern U.S. was repeatedly glaciated during the Pleistocene, resulting in a generally low-relief landscape (Kerr et al., 2021). Tallgrass prairie developed during the
Holocene and was the dominant ecosystem prior to European settlement in the late 1800s (Smith, 1990). The glacial history and vegetation led to the development of fertile soils that make the Midwest one of the world’s most productive agricultural regions. The region encompasses 20% of U.S. land area yet produces ~85% of all corn and soybeans harvested in the country (USDA, 2021). However, intensive agricultural land use has degraded soils, resulting in the removal of organic-carbon-rich A-horizon soils from 35±11% of the agricultural land area, which annually leads to $3 billion in losses due to decreased productivity (Thaler et al., 2021). Most prairies have been converted to agriculture, and only 0.1% of the original tallgrass prairie remains in several Midwestern states (Samson and Knopf, 1994). These native prairie remnants preserve the landscape and soil geochemistry that predate widespread land use change that occurred in the late 1800s.

We collected samples from 14 native prairie sites in the Midwest (Figure 1). Ten of the study sites have soils formed from glacial till deposited by the Marine Isotope Stage 2 (MIS2) Des Moines Lobe advance in Iowa and Minnesota and were deglaciated between 21.1 and 13.5 ka (Dalton et al., 2020). The Steinauer site in eastern South Dakota is near the margin of the James Lobe, and ice chronologies disagree on whether the site was glaciated during MIS2 (e.g., Batchelor et al., 2019; Dalton et al., 2020). The Hayden site is on the Iowan Surface and was most recently glaciated during MIS6 (58-72 ka) (Kerr et al., 2021; Batchelor et al., 2019). The Spring Creek site in southeastern Nebraska was glaciated only during MIS16 (622-677 ka) (Batchelor et al., 2019). A local till unit dates to 650 ka and is overlain by several loess units ranging in age from 580 to 12 ka (Balco et al., 2005). Loess thickness decreases to the southeast, however, and is locally discontinuous on steeper terrain (Mason et al., 2007; Soller et al. (2004) map the site as
silt-rich till. The Sheppard site in northeastern Kansas was most recently glaciated during MIS16 (Batchelor et al., 2019). Though much of Kansas is overlain by MIS2-age loess, Sheppard is in a loess-free area (Welch and Hale, 1987) and is mapped as silty till (Soller et al., 2004).

Figure 1. Locations of the 14 native prairie sites in the Midwestern U.S. The blue shading shows the extent of ice sheets during MIS2 (12-29 ka), MIS6 (58-72 ka), and MIS16 (622-677 ka). The blue line indicates maximum Pleistocene ice extent (Batchelor et al., 2019).
Methods

10Be Analyses

We used a hand auger to sample soil in 18 cm increments to a total depth of 2-4 m on the summits of convex hilltops. Samples from selected depth increments were split and sub-samples processed to generate pure quartz separates from 250-850 µm grains for in situ-produced 10Be extraction at the University of Massachusetts Cosmogenic Nuclide Laboratory (Kohl and Nishiizumi, 1992). 10Be/9Be ratios were measured via AMS at the Purdue Rare Isotope Measurement Laboratory and Lawrence Livermore National Laboratory (Table 1).

The measured nuclide concentrations (N) reflect inherited 10Be from prior exposure (N(0)), duration of exposure (t), and denudation rate (ε). We determined denudation rates corrected for inheritance (e.g., Anderson et al., 1996) and exposure age using the Monte Carlo depth profile method of Hidy et al. (2010) to solve the time-dependent, non-steady state nuclide concentration equation of Lal (1991):

\[
N(z, t) = N(z, 0) e^{-\lambda t} + \frac{P(0)}{\lambda + \frac{\rho z}{\Lambda}} e^{-\frac{\rho z}{\Lambda}} \cdot (1 - e^{-(\lambda + \frac{\rho z}{\Lambda})t})
\]

where \(P(0)\) is the surface production rate (atom g\(^{-1}\) yr\(^{-1}\)), \(\lambda\) is a decay constant (4.997 x 10\(^{-7}\) yr\(^{-1}\); Chmeleff et al., 2010), \(\rho z\) is depth-dependent bulk density (g cm\(^{-3}\)), \(\Lambda\) is attenuation length (160 g cm\(^{-2}\)), \(z\) is depth (cm), and \(t\) is time (yr). We calculated site production rates using the Hidy et al. (2010) method, which incorporates measurements of latitude, longitude, and elevation with a specified scaling scheme and reference spallation production rate. We used the scaling scheme of Stone (2000) after Lal (1991) and a 10Be reference production rate of 4.01 atoms g\(^{-1}\) yr\(^{-1}\) (Borchers et al., 2015). The Hidy et al. (2010) method also calculates muonic production based on a specified elevation and profile.
depth. We used a depth-dependent bulk density model, $\rho = 0.1909 \ln(z) + 0.9298$, based on bulk density samples collected from all sites and an uncertainty of 20% (Figure 2, Table 2). Many of our bulk density samples were dry when weighed; to correct for this we assumed an additional 10 weight percent saturation of dried samples, based on the water content of moist bulk density samples.

Exposure age, inheritance, and denudation rate are treated as unknowns in the Hidy et al. (2010) method, but the range of solutions can be constrained based on independent data. Hence, we used the measured $^{10}$Be concentration of the deepest sample in each profile as the upper-bound of the inherited $^{10}$Be concentration. We set the upper and lower bounds on exposure age using published deglaciation chronologies for each site (Table 3), which are tightly constrained for the Des Moines lobe (Dalton et al., 2020). $^{10}$Be concentrations on young landforms, such as Des Moines Lobe moraine deposits, are unlikely to be in steady state, which is explicitly accounted for in Equation 1.

We ran 100,000 Monte Carlo simulations for each site to obtain the most probable values for inheritance, exposure age, and denudation rate (Table 4). We use the Bayesian most probable results for exposure age and inheritance concentration since the Bayesian results more accurately represent the most probable solutions than do the mode results. For denudation rates, however, we use the mode because the Bayesian most probable denudation rate for Bernau and Kurtz is zero, which is incompatible with the non-zero chemical denudation indicated by geochemical mass balance at those sites.
Figure 2. Bulk density model and sample measurements. The model assumes 10 weight % saturation and is given by the function \( \rho = 0.1909 \ln(z) + 0.9298 \pm 20\% \), where \( \rho \) = bulk density (g cm\(^{-3}\)) and \( z \) = depth (cm). The horizontal bars represent 20% uncertainty in the density value and were selected to conservatively span the measured values.

For sites where bioturbation homogenized surface \(^{10}\)Be concentrations, we only used samples from below the depth of bioturbation to fit the depth profile (Figure 3). At Willis, samples between those at the surface (0-18 cm) and 270 cm depth yielded insufficient quartz for \(^{10}\)Be measurement. For the depth profile analysis, we shifted the surface sample concentration to a depth of 36 cm, i.e., near the base of the presumed bioturbation zone, to obtain a profile that more accurately reflects the relationship between concentration and depth.
Figure 3. $^{10}$Be depth profile results. Samples shown with open circles were not used in the depth profile fitting.
**Geochemical Mass Balance**

The $^{10}$Be-derived denudation rate quantifies the combined mass loss due to physical erosion and chemical weathering. To directly compare our measurements against previously measured agricultural erosion rates in the adjacent fields, we partitioned the denudation rates we measured into physical erosion rate and chemical denudation rate components. This relationship can be summarized as follows:

$$\varepsilon = E + W$$

(2)

where $\varepsilon$ is the denudation rate, $E$ is the erosion rate, and $W$ is the chemical weathering rate (Riebe et al., 2003). Here we use $\varepsilon$ to represent the denudation rate, rather than the more commonly used notation $D$, as we later use $D$ to refer to the topographic diffusion coefficient.

We measured the concentrations of major and trace elements in prairie depth profiles via X-ray fluorescence (XRF) (Tables 5 and 6). For each site we analyzed the surface sample and deepest sample to quantify chemical weathering. Additionally, we measured intermediate samples to create a partial weathering profile for Willis and every sample to create a full weathering profile for Kurtz and Sheppard, to evaluate the relative degree of weathering at sites last glaciated during MIS2 versus MIS16 (Figure 4). Dried samples were sieved to remove the >2mm fraction, crushed using a mortar and pestle, ground to a fine powder using a tungsten carbide ring mill, then pressed into pellets or fused for trace and major element analysis, respectively. Samples were analyzed in the Ronald B. Gilmore X-Ray Fluorescence Laboratory at UMass-Amherst.
Because chemical weathering removes mobile elements, it causes the progressive enrichment of chemically immobile elements within weathered soil (Riebe et al., 2003). By comparing the concentrations of an immobile element, Zr, in weathered soil and unweathered parent material, we calculated the chemical depletion fraction (CDF), or the percentage of denudation caused by chemical weathering, as follows:

$$\text{CDF} = 1 - \left( \frac{[\text{Zr}]_{\text{parent}}}{[\text{Zr}]_{\text{soil}}} \right)$$ (3)

where $[\text{Zr}]_{\text{parent}}$ and $[\text{Zr}]_{\text{soil}}$ are the concentrations of Zr in the parent material and soil, respectively (Riebe et al., 2003). We calculated a CDF for each site using the highest and lowest samples from the depth profiles as the soil and parent terms, respectively (Table 7). We then calculated the proportion of denudation caused by physical erosion and, thus, soil erosion rates.
Topographic Diffusion, Agricultural Erosion, and Soil Loss Tolerance

We calculated topographic curvature \(\frac{\partial^2 z}{\partial x^2}\) at each depth profile using 4 m resolution LiDAR-derived digital elevation models (DEMs) smoothed over a three-cell radius (e.g., Thaler et al., 2021) (Table 8). We plotted the physical erosion rate versus topographic curvature for each site, where, assuming erosion is governed by diffusive processes, the slope of the relationship describes the topographic diffusion coefficient, D (m\(^2\) yr\(^{-1}\)):

\[
\frac{\partial z}{\partial t} = D \frac{\partial^2 z}{\partial x^2}
\]  

(4)

where \(\frac{\partial z}{\partial t}\) is the landscape lowering rate in m yr\(^{-1}\) (Fernandes and Dietrich, 1997). We compared the pre-agricultural diffusion coefficient against agricultural diffusion coefficients that were measured in cultivated fields adjacent to our study sites to determine the magnitude of increased soil flux due to agriculture (Kwang et al., 2022; Thaler et al., 2022).

We used agricultural erosion rates from 11 of our study sites where Thaler et al. (2022) also measured soil loss via RTK GPS surveys of the escarpment between prairies and fields. We calculated time-averaged erosion rates for each site based on the thickness of soil loss and field cultivation history (Table 9). We determined soil loss tolerance (T) values for each site using the Gridded National Soil Survey Geographic (gNATSGO) Database (Soil Survey Staff, 2020). We converted T values from tons ac\(^{-1}\) yr\(^{-1}\) to mm yr\(^{-1}\) assuming an average topsoil bulk density of 1200 kg m\(^{-3}\) (e.g., Montgomery, 2007b; Thaler et al., 2022).
Results

$^{10}$Be depth profiles from our sites generally show an exponential decline in concentration with depth. Most sites show evidence of a mixing layer in the top 20-50 cm of soil. Depth profiles yielded mode denudation rates from 0.0002-0.18 mm yr$^{-1}$ with a mean of 0.07 mm yr$^{-1}$ (Table DR6). The mode and Bayesian most probable denudation rate results for each site are similar; we use mode values because the Bayesian most probable rate for Bernau and Kurtz is zero, which is not possible given the non-zero chemical weathering at the sites. Zr concentration analysis yielded chemical depletion fractions (CDFs) of 0.10-0.50 with a mean of 0.33. Physical erosion rates, calculated from denudation rates and CDFs, range from 0.0001-0.11 mm yr$^{-1}$ with a mean of 0.05 mm yr$^{-1}$ (Figure 5). In comparison, soil loss tolerance values assigned to these locations are 1 mm yr$^{-1}$. 
Exposure age results from our depth profile analysis support the inclusion of Steinauer within the limits of the MIS2 James Lobe; the age for the site, 12.8 ka, is at the lower limit of the $^{14}$C uncertainty of a possible southward resurgence of the James Lobe between 13 and 12 ka $^{14}$C (~15.5-14.2 calendar years ka) (Dalton et al., 2020). Hayden has an exposure age of 70 ka, placing it near the older limit of MIS 6 glaciation. Spring Creek has a probable age of 655 ka, in close agreement with the 650 ka age of nearby till (Balco et al., 2005). Sheppard has an older exposure age of 868 ka, i.e., MIS20/24; while Batchelor et al. (2019) show the site was glaciated during that time, they also show that the site was covered by ice more recently during MIS-16. There is poor agreement between exposure
age mode and Bayesian most probable values for the site, however, lending less certainty to our age results for the site.

Based on the inheritance-corrected surface concentrations and probable exposure ages from our depth profile analysis, most of our sites have not yet reached isotopic equilibrium (Figure 6). Spring Creek and Sheppard have sufficient exposure ages to have reached isotopic steady state despite their low denudation rates. The MIS2-age sites and Hayden, however, have had insufficient irradiation time for surface $^{10}\text{Be}$ concentrations to reach steady state. $^{10}\text{Be}$ concentrations at the more recently glaciated sites therefore reflect both exposure duration and denudation rate.

![Figure 6](image.png)

Figure 6. $^{10}\text{Be}$ surface concentrations as a function of time for different steady-state denudation rates predicted using eq. 1 (lines) and inheritance-corrected values from our depth profile $^{10}\text{Be}$ measurements (circles) for all sites (A) and MIS2 sites (B).

Sites with more convex curvature have generally higher erosion rates (Figure 7, Table DR7). The slope of the line relating curvature and erosion rates is the diffusion coefficient; a regression analysis yielded a diffusion coefficient of 0.005 (±0.002) m$^2$ yr$^{-1}$
with a y-intercept of 1.8x10^{-5} (±1.3x10^{-5}) and R^2 of 0.41. The intercept is not statistically different from zero (p-value=0.2, α = 0.05), supporting the assumption that prairie erosion is dominated by hillslope diffusion.

Agricultural erosion rates from paired field sites are 0.59 to 4.90 mm yr^{-1}, with a mean of 2.27 mm yr^{-1} (Thaler et al., 2022; Table DR8). A comparison of pre-agricultural and agricultural erosion rates indicates that fields are eroding 10 to >1000 faster than natural rates of soil erosion (Figure 7).

![Figure 7](image)

**Discussion**

Due to the young exposure ages of MIS2 sites and Hayden, site ^{10}Be surface concentrations have not reached steady state; thus small variation in ^{10}Be concentrations can translate to large differences in erosion rate (Figure 6b). For example, surface concentration uncertainty in the Stinson site on the Des Moines Lobe spans erosion rates
of 0.001-0.1 mm yr\(^{-1}\). Additionally, sites such as Judson and Blue Gentian have \(^{10}\)Be depth profiles that deviate from the theoretically predicted exponential function, possibly due to deep bioturbation, and have predicted erosion rates of \(~0.1\) mm yr\(^{-1}\), which are high for low-relief continental interiors (Larsen et al., 2014). Erosion rates for the two sites to have reached steady state, Spring Creek and Sheppard, are among the lowest (<0.01 mm yr\(^{-1}\)) and are more precisely constrained than other sites. Furthermore, Hidy et al. (2010) note that depth profile solutions skew toward maximum erosion rates. It is therefore possible that our analysis overestimates true erosion rates for MIS2 sites. Nonetheless, the pre-agricultural erosion rates are orders of magnitude lower than agricultural rates measured in cultivated fields adjacent to the native prairies we sampled.

The pre-agricultural diffusion value we calculated from erosion rates is 0.005 m\(^2\) yr\(^{-1}\). In contrast, agricultural diffusion coefficients from Kwang et al. (2022) and Thaler et al. (2022) for the region are 0.14–0.40 m\(^2\) yr\(^{-1}\). Thus agricultural practices, such as tillage, increase diffusion by two orders of magnitude, resulting in increased rates of soil loss from convex hillslopes in cultivated fields. The >10 to >1000-fold increase in erosion rates due to agriculture we document is similar to increases inferred from global compilations (e.g., Montgomery, 2007b), but because most areas lack quantitative constraints on pre-agricultural erosion rates, our findings provide one of the first assessments of agriculturally accelerated erosion rates in a major agricultural region.

The presence of thick, organic carbon-rich soil horizons at the native prairie sites indicates that time-averaged soil production rates are equal to, or greater than, natural denudation rates. If the soil profiles have reached steady state, i.e., constant soil thickness over time, the rate that soil is removed must be equal to the rate at which it is produced
(Heimsath et al., 1997). Our sites differ from those where most soil production rates have been measured, however, as soil is forming primarily from glacial till and the distinction between soil and parent material is defined by gradational changes in chemical weathering rather than a soil to bedrock transition. Weathering profiles show comparable depths of Zr enrichment for soils of different ages, of ~1 m for the Des Moines Lobe sites Kurtz and Willis as well as the much older Sheppard site. It is therefore possible that even the younger sites have had sufficient time to reach a steady state weathering zone thickness, and that the denudation rates we measure are equivalent to soil production rates. Quantifying natural denudation may therefore also constrain the rate of soil formation. Regardless of whether the $^{10}$Be concentrations can be strictly interpreted as soil production rates, the presence of thick, organic carbon-rich soil horizons in the native prairies indicates that biologically productive soils are maintained at the low natural erosion rates we measure.

Despite the development of soil loss tolerance values, Midwestern soil loss literally outweighs the mass of crops produced (Nearing et al., 2017). Soil loss tolerance values assigned to our sites are 1 mm yr$^{-1}$, one to four orders of magnitude higher than the pre-agricultural erosion rates we measured. Moreover, agricultural erosion rates from 9 out of 11 paired field-prairie sites exceed soil loss tolerance values. Therefore not only are current agricultural erosion rates unsustainable, but even reducing erosion to “tolerable” rates would result in soil loss orders of magnitude greater than natural rates. Evidence from modern fields demonstrates that agricultural land use has caused the complete removal of A-horizon soil from much of the landscape in only about 150 years (Thaler et al., 2021). The thick A-horizons that we observed at the prairies, however, demonstrate that low rates of natural erosion can maintain high levels of soil fertility over the lifetime of the soils, i.e.,
tens to hundreds of thousands of years. Thus, a lower soil loss tolerance value in line with pre-agricultural erosion rates would ensure the preservation of soil resources indefinitely. No-till farming can reduce erosion to levels similar to the pre-agricultural rates we measured (Montgomery, 2007b). Hence, using cosmogenic nuclides to establish lower T values, and incentivizing practices that accordingly reduce erosion rates, would better sustain soil resources in the Midwest.

**Conclusions**

We find pre-agricultural erosion rates on the order of 0.0001-0.1 mm yr\(^{-1}\). The presence of thick soil A-horizons that we observed at the prairie sites demonstrates that low pre-agricultural erosion rates can maintain high levels of soil carbon and fertility. However, soil loss tolerance values assigned to these locations are 1 mm yr\(^{-1}\), one to four orders of magnitude higher than pre-agricultural erosion rates. Likewise, agricultural erosion rates measured in neighboring fields are 10 to >1000 times greater than the pre-agricultural erosion rates we measured in prairies, and often exceed soil loss tolerance values.

Erosion in much of the Midwest’s most densely cultivated cropland exceeds established soil loss tolerance values (Soil Survey Staff, 2020). T values at our sites exceed natural erosion rates by orders of magnitude, raising doubt as to the accuracy of T values and their ability to guide sustainable agricultural practices. Tolerable soil erosion, as currently defined, will lead to the depletion of Midwestern soils. It is therefore essential to quantitatively determine natural erosion and soil formation rates in Midwestern cropland to determine more realistic soil loss tolerance values. Quantifying natural erosion rates via
cosmogenic nuclides offers a means for developing scientifically-based soil management guidelines that can sustain soils and preserve agricultural productivity.

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