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Pre-agricultural soil erosion rates in the midwestern United States

Caroline L. Quarrier[1], Jeffrey S. Kwang[1,2], Brendon J. Quirk[1,3], Evan A. Thaler[1,4] and Isaac J. Larsen[1]
[1]University of Massachusetts Amherst, Department of Geosciences, Amherst, Massachusetts 01003, USA
[2]Department of Earth and Environmental Sciences, University of Minnesota, Minnesota 55455, USA
[3]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, Indiana 47907, USA
[4]Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

ABSTRACT

Erosion degrades soils and undermines agricultural productivity. For agriculture to be sustainable, soil erosion rates must be low enough to maintain fertile soil. Hence, quantifying both pre-agricultural and agricultural erosion rates is vital for determining whether farming practices are sustainable. However, there have been few measurements of pre-agricultural erosion rates in major farming areas where soils form from Pleistocene deposits. We quantified pre-agricultural erosion rates in the midwestern United States, one of the world's most productive agricultural regions. We sampled soil profiles from 14 native prairies and used *in situ*–produced ^{10}Be and geochemical mass balance to calculate physical erosion rates. The median pre-agricultural erosion rate of 0.04 mm yr^{-1} is orders of magnitude lower than agricultural values previously measured in adjacent fields, as is a site-averaged diffusion coefficient (0.005 m^2 yr^{-1}) calculated from erosion rate and topographic curvature data. The long-term erosion rates are also one to four orders of magnitude lower than the assumed 1 mm yr^{-1} soil loss tolerance value assigned to these locations by the U.S. Department of Agriculture. Hence, quantifying long-term erosion rates using cosmogenic nuclides provides a means for more robustly defining rates of tolerable erosion and for developing management guidelines that promote soil sustainability.

INTRODUCTION

Agricultural erosion degrades soil and reduces crop productivity. The cost of soil erosion in the United States 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 (Amundson et al., 2015). Soils contain about three times more carbon than the atmosphere; hence, quantifying erosion rates is essential for understanding the role soils play in the carbon cycle (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 comparable to rates of geological erosion and soil formation (Montgomery, 2007; Wilkinson and McElroy, 2007). However, agricultural practices erode soil at rates 10 to more than 100 times greater than pre-agricultural levels (Montgomery, 2007; Nearing et al., 2017). In the early 20th century, recognition of the imbalance between rates at which soil forms and is eroded led the U.S. Department of Agriculture to develop soil loss tolerance (T) values for croplands, which delimit maximum erosion rates that can be tolerated without loss of agricultural productivity (Smith, 1941). However, scientists could only speculate about the rates at which soil formed from parent materials at that time, and subsequently many have suggested that T values are too high (e.g., Johnson, 1987; Schertz and Nearing, 2006; Li et al., 2009).

Cosmogenic nuclides, such as ^{10}Be, are routinely used for measuring long-term denudation and soil production rates. ^{10}Be-derived denudation rates have been compared against contemporary sediment yield or soil erosion measurements to quantify increases in soil erosion due to agriculture (e.g., Brown et al., 1998; Vanacker et al., 2007; Reusser et al., 2015; Evans et al., 2019), and these studies demonstrated that agriculture increases erosion by orders of magnitude. However, except for data from a few recent studies in Germany (Calitri et al., 2019), Minnesota, USA (Jelinski et al., 2019), and Poland (Loba et al., 2021), there is little quantitative information regarding long-term rates of 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.

We used *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 United States. We calculated a pre-agricultural topographic diffusion coefficient from the erosion rate and topographic curvature data. We then compared the long-term, pre-agricultural erosion rates and diffusion coefficient against those previously measured in adjacent agricultural fields to assess whether T values for each site are adequate for sustaining soils.

STUDY SITE

The midwestern United States was repeatedly glaciated during the Pleistocene, resulting in a generally low-relief landscape. 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 Midwest encompasses 20% of U.S. land area yet produces ~85% of all corn and soybeans harvested in the country (USDA, 2021). However, intensive farming has degraded soil on one-third of cropland (Thaler et al., 2021). Most native prairies have been converted to agriculture; in some states, only 0.1% of the original tallgrass prairie remains (Smith, 1990). These prairie remnants preserve the landscape and soil geochemistry that predate region-wide land use change. The prairie soils are rich in organic carbon relative to adjacent cropland soils (Kwang et al., 2022). Because organic carbon content is a primary determinant of soil productivity (Montgomery, 2007), we infer that

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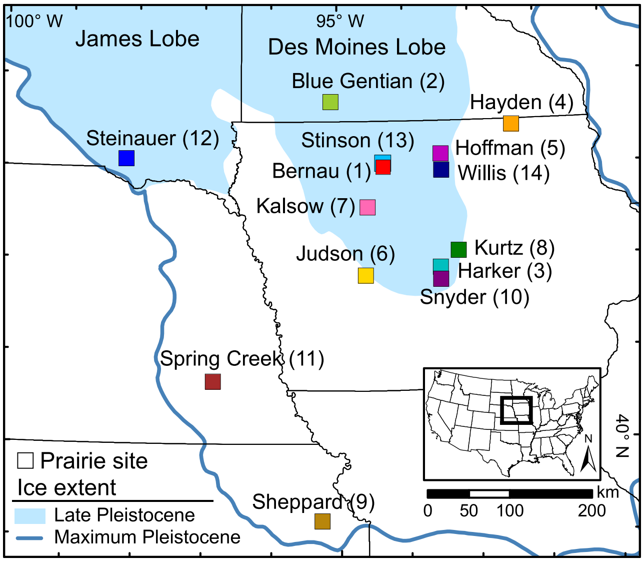

Figure 1. Locations of the study sites; numbers match those in Figures 2–4. Blue shading shows the extent of glaciation during the late Pleistocene (Marine Isotope Stage 2; 12–29 ka); the blue line indicates maximum Pleistocene ice extent.

pre-agricultural erosion rates are low enough to sustain productive soils.

We collected samples from 14 native prairies in the Midwest (Fig. 1). Soils at 10 of the sites formed from glacial till deposited during the Marine Isotope Stage 2 (MIS 2) Des Moines Lobe advance in Iowa and Minnesota, and were deglaciated between 21.1 ka and 13.5 ka (Dalton et al., 2020). The Steinauer site in South Dakota, at the margin of the James Lobe, was also glaciated during MIS 2 (Kerr et al., 2021). The Hayden site on the Iowan Surface was glaciated prior to MIS 8, >200 ka (Kerr et al., 2021), and the age of the deposits are not well-constrained. Ice sheet reconstructions suggest the Spring Creek site in Nebraska was glaciated during MIS 16 (622–677 ka; Batchelor et al., 2019). The site is mapped as silt-rich till (Soller et al., 2004) and till at a nearby site dates to 650 ka (Balco et al., 2005). The Sheppard site in Kansas is also predicted to have been glaciated during MIS 16 (Batchelor et al., 2019) and is in a loess-free area (Welch and Hale, 1987) mapped as silty till (Soller et al., 2004).

METHODS

We used a hand auger to sample soil and underlying till in 18 cm increments to a total depth of 2–4 m on the summits of convex hilltops. Samples from selected depth increments were subsampled and processed to generate pure quartz for *in situ*–produced ^{10}Be extraction at the University of Massachusetts (Amherst, USA). $^{10}Be/^{9}Be$ ratios were measured via accelerator mass spectrometry at the Purdue Rare Isotope Measurement Laboratory (Indiana, USA) and at Lawrence Livermore National Laboratory (California, USA) (Table S1 in Supplemental Material[1]).

The measured nuclide concentrations reflect the combined contributions of inherited ^{10}Be from prior exposure, the duration of current exposure, and the denudation rate. We determined the contributions of inheritance, exposure age, and denudation rate using the Monte Carlo method of Hidy et al. (2010), which solves the non-steady state ^{10}Be concentration equation of Lal (1991) by finding parameters that best fit measured ^{10}Be concentration depth profiles. The exposure age, inheritance, and denudation rate are treated as unknowns, but the range of solutions can be constrained based on independent data (Hidy et al., 2010). 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. The upper and lower bounds on exposure age were assigned using known deglaciation chronologies for each site (Table S2), which are constrained to within a few thousand years for sites on the Des Moines Lobe by ^{14}C isochrone data (Dalton et al., 2020), but are less well-constrained at the other sites.

To directly compare our results with previously measured agricultural erosion rates, which occur via physical soil transport processes (von Blanckenburg, 2005), we partitioned our measured denudation rates into physical erosion rate and chemical weathering rate components. We first measured the concentration of the chemically immobile element Zr via X-ray fluorescence spectroscopy (XRF) analysis of the uppermost and lowermost samples in each profile, which we assume are representative of the weathered soil and unweathered parent material, respectively. We then used the enrichment of Zr in soil relative to parent material to calculate the chemical depletion fraction (CDF), which is the fraction of denudation caused by chemical weathering (Riebe et al., 2003). We multiplied the CDF by the ^{10}Be-based denudation rate to quantify the chemical weathering rate and then calculated the physical erosion rate by subtracting the chemical weathering rate from the denudation rate. We also measured Zr concentrations of the entire depth profile at the Kurtz and Sheppard sites to evaluate the relative degree of weathering at sites last glaciated during MIS 2 versus MIS 16 (Fig. S1). Details of sample processing and analysis are described in the Supplemental Material.

We calculated topographic curvature at each depth profile using 4-m-resolution lidar-derived digital elevation models that were smoothed over a three cell radius, as described by Thaler et al. (2021). We plotted the physical erosion rate versus topographic curvature for each site. Assuming that erosion is governed by diffusive processes, the slope of the relationship is the topographic diffusion coefficient (e.g., Thaler et al., 2022). We compared the pre-agricultural diffusion coefficient against agricultural diffusion coefficients that were measured in cultivated fields adjacent to our prairie study sites (Kwang et al., 2022; Thaler et al., 2022) and compared the pre-agricultural erosion rates against agricultural erosion rates measured in 11 adjacent fields (Thaler et al., 2022). T values for each site were determined using the Gridded National Soil Survey Geographic Database (Soil Survey Staff, 2020). We converted T values to units of mm yr^{-1} using a soil bulk density of 1120 ± 400 kg m^{-3}, which is the mean and standard deviation of 1229 measurements from our study region (Soil Survey Staff, 2013).

RESULTS

^{10}Be depth profiles from our sites generally show an exponential decline in concentration with depth, and there is evidence of a mixing layer in the uppermost 20–50 cm at most sites (Fig. S2). The modal denudation rates from 100,000 Monte Carlo simulations for each depth profile are 0.0002–0.18 mm yr^{-1}, with a median of 0.06 mm yr^{-1} (Table S3). Chemical depletion fractions range from 0.10 to 0.50 with a median of 0.33 (Table S4). Physical erosion rates range from 0.0001 mm yr^{-1} to 0.11 mm yr^{-1} with a median of 0.04 mm yr^{-1} (Fig. 2). The T-value for all sites is 1 mm yr^{-1}. The ^{10}Be results indicate that the sites with older glacial advances have been deglaciated for long enough to have achieved steady-state ^{10}Be concentrations (cf. Lal, 1991), whereas ^{10}Be concentrations at the more recently glaciated (MIS 2) sites are still increasing (Fig. 3).

Sites with more convex topography (more negative curvature) generally have higher erosion rates (Fig. 4A). Regression analysis yields a slope or diffusion coefficient of 0.005 ($\pm$0.002) m^2 yr^{-1} with a *y*-intercept of 1.6×10^{-5} ($\pm 1.3 \times 10^{-5}$) m yr^{-1} and R^2 of 0.43. In a landscape that is eroding purely by

[1]Supplemental Material. Methodological details, supplemental figures, and Tables S1–S9. Please visit https://doi.org/10.1130/GEOL.S.21200461 to access the supplemental material, and contact editing@geosociety.org with any questions.

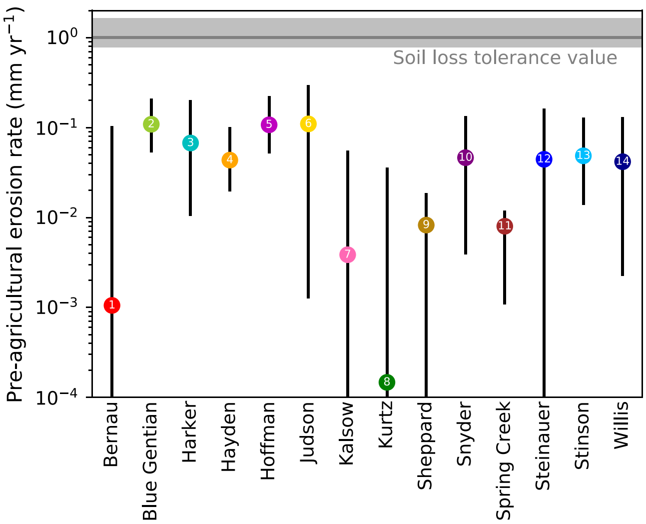

Figure 2. Pre-agricultural erosion rates and soil loss tolerance values (T values) for all sites in the midwestern United States (see Fig. 1 for locations). Circles indicate modes (the most frequent result from the Monte Carlo analysis); error bars denote 2σ uncertainty. Gray shading shows the range of T values based on 1σ variability in soil bulk density.

diffusion, there is no erosion where curvature is zero. The intercept is not statistically different from zero (p-value = 0.2, α = 0.05), which supports the assumption that erosion at hilltop summits in the prairies is diffusion-dominated. Agricultural erosion rates from adjacent fields are ~10–1000 times higher than pre-agricultural soil erosion rates (Fig. 4B).

DISCUSSION

Due to the young ages of the MIS 2 sites, ^{10}Be surface concentrations there have not reached steady state. The age of the landforms is well-constrained, which allows interpretation of the ^{10}Be concentrations as denudation rates. However, the results plot in the portion of concentration-exposure age space where a small variation in ^{10}Be concentration can translate to a large difference in denudation rate (Fig. 3B). For example, 2σ uncertainty in the denudation rate at the Stinson site on the Des Moines Lobe spans 0.001–0.1 mm yr^{-1}, and the upper-bound value is high for low-relief continental interiors (Larsen et al., 2014). Erosion rates for two of the three sites that have most clearly achieved steady-state ^{10}Be concentrations, Spring Creek and Sheppard, are among the lowest (<0.01 mm yr^{-1}) and are more precisely constrained than at other sites. The depth profile solutions also skew toward maximum denudation rates (Hidy et al., 2010). Hence, it is possible that our analysis overestimates true erosion rates for some of the sites. Nonetheless, the pre-agricultural erosion rates are orders of magnitude lower than agricultural rates measured in cultivated fields adjacent to the native prairies, and the 10–1000-fold increase in erosion rates due to agriculture is similar to increases inferred from global compilations (e.g., Montgomery, 2007).

Diffusivity data are required to implement models that predict the redistribution of soil and carbon as landscapes evolve (e.g., Kwang et al., 2022). There are few estimates of pre-agricultural diffusion coefficients in landscapes formed by erosion of glacial till; hence, the pre-agricultural diffusion coefficient of 0.005 m^2 yr^{-1} is one of the first estimates for this type of landscape. The value is about two orders of magnitude lower than agricultural diffusion coefficients of 0.14–0.40 m^2 yr^{-1} measured in adjacent fields (Kwang et al., 2022; Thaler et al., 2022), which is expected, given the large difference in erosion rates and generally similar topographic curvature.

In landscapes where soil thickness reaches steady state, denudation rates can be interpreted to be equivalent to the rate at which soil or mobile regolith is produced from underlying rock (Heimsath et al., 1997). Our sites differ from those where most soil production rates have been measured, as soil is forming primarily from glacial till, and the distinction between soil and parent material is defined by gradational changes in the degree of chemical weathering rather than a soil-to-bedrock transition. Zr enrichment extends to comparable depths of ~1 m at the Kurtz site on the Des Moines

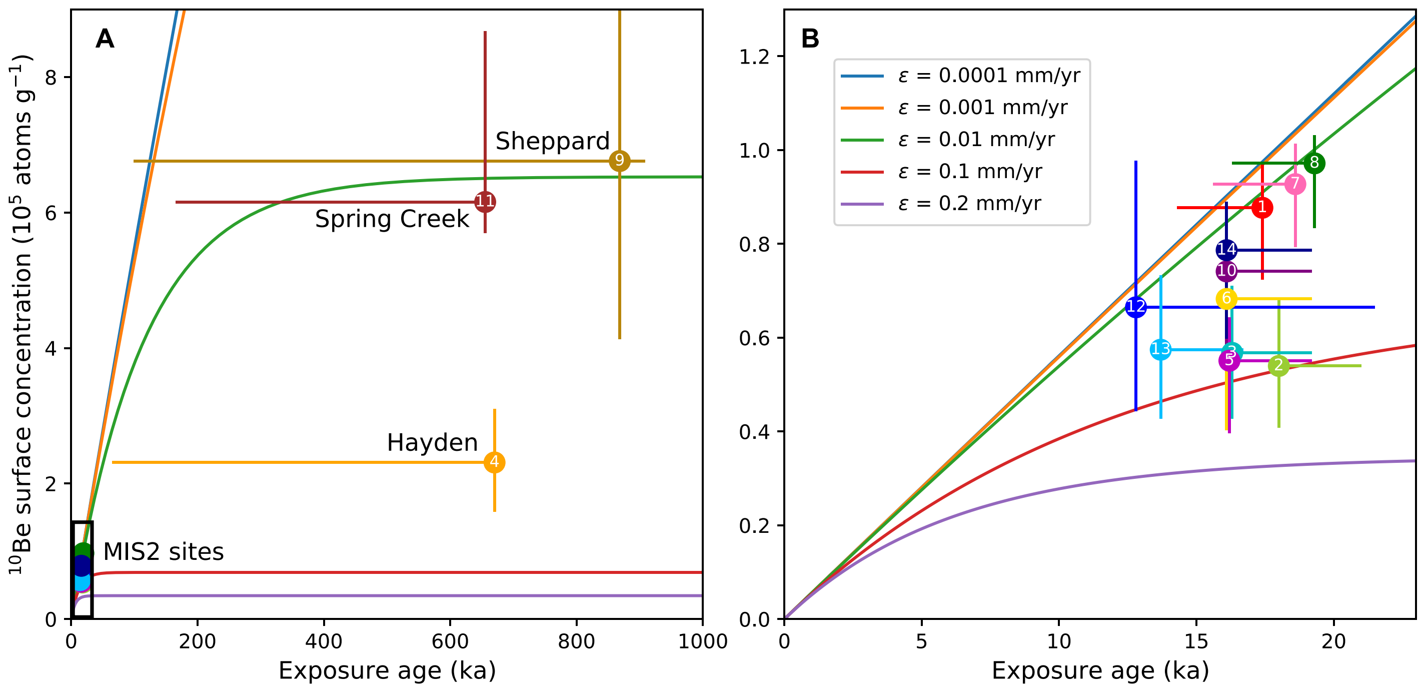

Figure 3. ^{10}Be surface concentrations as a function of time for different steady-state denudation rates (lines), and inheritance-corrected values from our depth profile ^{10}Be measurements (circles) for (A) all sites and (B) sites last glaciated during MIS 2 (see Fig. 1 for site locations). Error bars denote 2σ uncertainty.

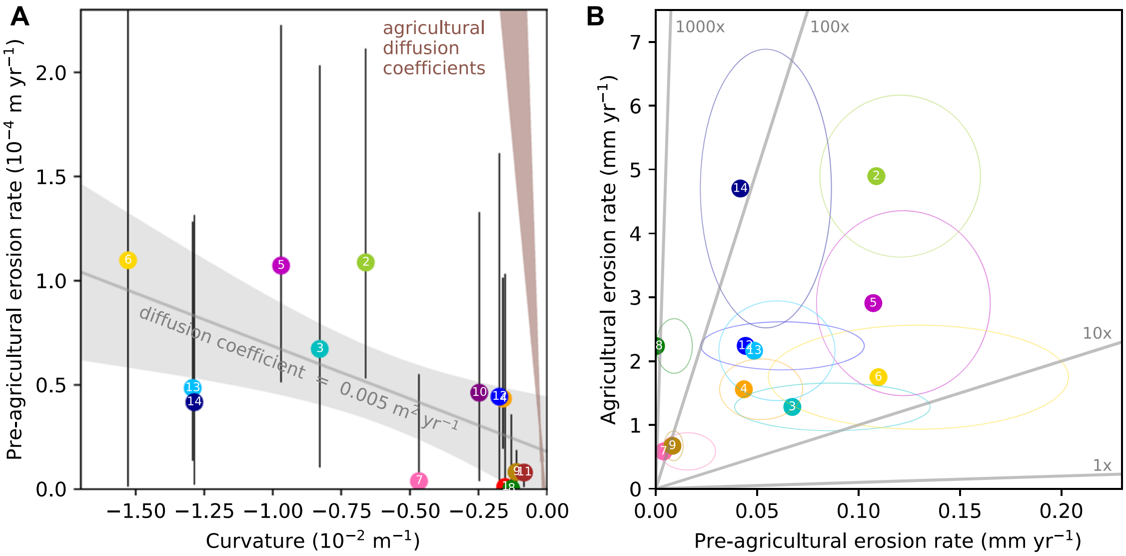

Figure 4. (A) Pre-agricultural erosion rate versus topographic curvature. The regression slope of 0.005 m^2 yr^{-1} is equal to the diffusion coefficient. Error bars and gray shading denote 2σ uncertainty, and brown shading shows the range of agricultural diffusion coefficients for adjacent fields. (B) Agricultural erosion rates measured at 11 of our 14 study sites (see Fig. 1 for site locations) (Thaler et al., 2022) versus pre-agricultural erosion rates. The error ellipses denote 1σ uncertainty.

Lobe and the Sheppard site in Kansas, where we estimate that time since deglaciation varies by 0.85 Ma. Hence, it is possible that the weathering zone has reached a steady-state thickness, even at the younger sites, and that the denudation rates we measured are equivalent to soil production rates. However, regardless of whether the ^{10}Be concentrations can be strictly interpreted as soil production rates, or simply as long-term denudation rates, the presence of thick, organic carbon–rich soil horizons in the native prairies indicates that biologically productive soils are maintained at the erosion rates inferred from the ^{10}Be concentrations. No-till farming can reduce erosion to levels similar to the pre-agricultural rates we measured (Montgomery, 2007). Hence, using cosmogenic nuclides to determine tolerable soil erosion rates, and incentivizing practices that reduce erosion rates accordingly, such as no-till, would better sustain soil resources in the Midwest.

CONCLUSIONS

We find that pre-agricultural erosion rates in the midwestern United States are on the order of 0.0001–0.1 mm yr^{-1}. Soil loss tolerance values of 1 mm yr^{-1} are one to four orders of magnitude higher than pre-agricultural erosion rates. Similarly, the agricultural erosion rates are 10–1000 times greater than the pre-agricultural erosion rates. Our results indicate that tolerable soil erosion, as currently defined, will lead to the depletion of midwestern soils. However, quantifying pre-agricultural erosion rates via cosmogenic nuclides and geochemical mass balance offers a means for developing improved soil management guidelines that can sustain soils and agricultural productivity.

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