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Acceleration of Soil Erosion by Different Land Uses in Arid Lands above \(^{10}\)Be Natural Background Rates: Case Study in the Sonoran Desert, USA

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Abstract: Land use changes often lead to soil erosion, land degradation, and environmental deterioration. However, little is known about just how much humans accelerate erosion compared to natural background rates in non-agricultural settings, despite its importance to knowing the magnitude of soil degradation. The lack of understanding of anthropogenic acceleration is especially true for arid regions. Thus, we used \(^{10}\)Be catchment averaged denudation rates (CADRs) to obtain natural rates of soil erosion in and around the Phoenix metropolitan region, Arizona, United States. We then measured the acceleration of soil erosion by grazing, wildfire, and urban construction by comparing CADRs to erosion rates for the same watersheds, finding that: (i) grazing sometimes can increase sediment yields by up to 2.3–2.6x, (ii) human-set wildfires increased sediment yields by up to 9.7–10.4x, (iii) after some post-fire vegetation recovered, sediment yield was then up to 4.2–4.5x the background yield, (iv) construction increased sediment yields by up to 5.0–5.6x, and (v) the sealing of urban surfaces led to one-tenth to one-half of the background sediment yields. The acceleration of erosion at the urban–rural interface in arid lands highlights the need for sustainable management of arid-region soils.

Keywords: \(^{10}\)Be denudation rates; arid lands; grazing; land use changes; land degradation; natural background rate; soil erosion; wildfire; urban construction

1. Introduction

The scholarly study of soils and their geographical variability rests at the nexus of a variety of disciplines, including agronomy, botany, geology, forestry, planning and development, religious studies, the Soviet tradition of landscape science, water science and technology, and, at its core, physical geography [1,2]. Soil erosion studies are just as interdisciplinary, as reflected in a recent analysis of citation patterns [3]. This high level of interest in soils and soil erosion can be explained by the critical functions and services for societies and natural environments that soils provide [4–9].

A fundamental reality is that soils develop over \(10^3–10^6\) year timescales [10]. Yet, land use land cover changes (LULCCs) on timescales of \(10^1–10^2\) years greatly increase soil erosion [11–26]. Unfortunately, the continued existence of soils requires that the rate of replenishment be equal to or greater than the rate of erosion [27].

Cosmogenic nuclides have revolutionized the study of earth surface processes [28], including soil erosion, by analyzing the cosmogenic nuclide \(^{10}\)Be in quartz at the mouths
of catchments [10,27]. Catchment averaged denudation rates (CADRs) provide an understanding of erosion rates over timescales of $10^3$–$10^5$ years. This allows for comparisons between modern and natural background erosion rates. For example, agricultural fields erode soils 1–2 orders of magnitude greater than natural rates [29,30].

Poesen [31] advocated for the importance of research to develop a better understanding of both natural and anthropogenic soil erosion. Thus, here, we compare modern rates of soil erosion to natural background rates (CADRs). Our regional focus is the northeast Sonoran Desert of western North America—the area in and around the Phoenix metropolitan region (PMR), Arizona, United States [32]. Prior research [33] analyzed over two decades of soil erosion in the PMR, comparing the impacts of urbanization, wildfire, and grazing—key processes leading to soil erosion [22]; wildfires [34,35]; and overgrazing [36]). Nearing et al. [37] reviewed natural and anthropogenic rates of soil erosion in the United States and northeastern China using geologic rates of soil erosion that included $^{10}$Be CADRs. Here, we focus our research on the exact same catchments where we obtain background rates of soil erosion from CADRs and also modern soil erosion from urbanization, wildfire, or grazing in an arid region.

2. Study Area

The Sonoran Desert in central Arizona (Figure 1) is classified as having a Köppen–Geiger climate. A 100-year climate record (1895–1998 CE) from Phoenix, Arizona, United States shows that the annual precipitation averages 202 mm and the average temperatures range from 6 °C in January to 41 °C in July [38]. Bimodal rainfall occurs in winter (November to March) from cold fronts and in July and August from the North American monsoon [39].

Our research focuses on 18 stock ponds located on the margins of Phoenix’s urban sprawl (Figure 2). Berms were constructed in the 1950s and 1960s, blocking small drainages in order to collect water for cattle. We previously collected data from over two decades of soil erosion in the small watersheds of these stock ponds as well as monitored land use land cover changes (LULCCs), including grazing, wildfires, and urban construction [33]. For this study, we collected CADR samples from these same catchments to permit a direct comparison between modern and natural erosion rates. Our strategy of using artificial dams is certainly not unique. Vaezi et al. [40], for example, calculated the sediment yield in twenty small catchments by measuring the sediment mass that accumulated behind check dams in northwest Iran.
Figure 1. Topography of Arizona, United States with the studied watersheds found within the box. This study area occurs in the climatological Sonoran Desert and within a geological Basin and Range Province where the Salt, Verde, and Gila rivers flow through the Phoenix metropolitan region, Arizona, United States.

Figure 2. The urban sprawl of the Phoenix metropolitan region from 1912 to 2010 provides context for the locations of the 18 monitored stock pond catchments in the Sonoran Desert, United States. Urban boundaries were extracted from a land cover classification by Central Arizona–Phoenix Long-Term Ecological Research. Numbers match to the stock ponds identified in Tables 2 and 4.
This study site section places the 18 stock pond study sites (Figure 3) within the context of broader issues of soil erosion in the Phoenix metropolitan region (PMR). Similar to Mohammed et al.’s study [41] in Syria, Jeong and Dorn [33] found that different LULCCs in the PMR increased historic erosion rates. Thus, this section provides regional background on the key PMR LULCCs of (i) grazing; (ii) wildfires; and (iii) exposure of bare ground due to urbanization.

Figure 3. Metropolitan Phoenix, framed by the box in Figure 1. (A) Location of catchments studied by $^{10}$Be CADRs where numbers correspond to Tables 3 and 6. (B) Basic geologic map of the composition of bedrock ranges. The study sites are located on piedmonts of these ranges, both pediments and alluvial fans, experiencing urban sprawl.

Grazing impacts erosion processes in our watersheds by reducing vegetation cover and by the removal of biological soil crusts (BSCs) that once protected desert surfaces from wind and water erosion [42,43]. Naturally, BSCs were much more extensive in the region [44], but currently remain only as isolated patches—all due to human-induced disturbances such as cattle grazing [32]. The removal of BSCs means that the dominant processes of grain detachment and transport that we observed directly during the two-decade study were rainsplash [45] and overland flow.

Gullying is a key soil erosion process [20,46,47]. However, we did not observe gullying during our two decades of field observations in the studied watersheds [33]. Similarly, slope
can be a critical control on soil erosion [41,48,49]. Jeong and Dorn [33], however, did not find a statistically significant correlation between sediment yield and typical catchment properties, including slope, relief, drainage area, and drainage density, with possible reasons being the greater importance of LULCCs and also relatively small differences in these morphometric factors between the different PMR catchments.

Wildfire did not occur naturally in the Sonoran Desert during the Holocene [50]. Even though lightning strikes occur in the region during the North American monsoon summer season, sparse vegetation cover naturally inhibited the spread of fires in the Sonoran Desert [50]. This condition changed with the invasion of exotic annual grasses such as Bromus tectorum and Bromus madritensis ssp. Rubens that altered natural grass/fire cycles [51]. For example, D’Antonio and Vitousek [52] reported that the replacement of native shrublands by invasive grasses produced an abundance of fuels followed by an increasing frequency of large fires. Furthermore, after fires, invasive grasses typically thrive, leading to a fire regime that did not previously exist naturally [53]. Along with the urban sprawl’s encroachment on our studied catchments (Figure 1) came enhanced recreation by the urban population, including gun target shooting, off-road vehicle use, and, in particular, cigarette smoking by these users—a formula for wildfires that periodically consumed the studied watersheds.

With the advent of air conditioning, after World War II, the PMR rapidly expanded due to migrants seeking work, affordable housing, health in the warm dry desert, retirement, and an outdoor lifestyle [54]. Urban expansion mapped in Figure 2 prior to the 1950s took place on flat agricultural fields. Subsequent urban sprawl crept out onto the piedmonts of desert mountain ranges, both pediments and alluvial fans [32]. The 18 stock pond watersheds (Figures 2 and 3) are located on pediments and fans with a variety of rock types (Figure 3). Urban sprawl in the Sonoran Desert (Figure 2) increased the region’s vulnerability to erosion through construction, exposing bare ground to rainfall and runoff [32,55].

3. Materials and Methods

The first two parts of this section detail our approach to measuring background CADRs, first testing whether human-induced erosion impacts CADRs in the Sonoran Desert and then measuring CADRs for each of the 18 PMR catchments. The third part of this section then explains a statistical analysis of CADRs and morphometric characteristics of the catchments. The last part summarizes modern sediment yield data presented in detail in Jeong and Dorn [33] and how we compare those data with CADRs for the same catchments.

3.1. Test Experiment for Assessing the Effect of Human Activities on CADRs

The general observation amongst geomorphologists using $^{10}$Be to measure rates of erosion is that human activities do not influence CADRs [56]. This observation was true in a study of a mountainous watershed in the Phoenix area [57]. However, we felt it prudent to test whether aggressive urbanization in the form of a housing development might generate enough sediment to alter CADRs. Thus, we designed an experiment.

The idea of this test was to find a watershed that had its upper region in a natural preserve with a lower region experiencing rapid urbanization. In addition, the idea was for the watershed to have slopes that were on the steeper end of the Phoenix area, in order to accelerate potential differences in CADRs. In other words, if the CADR technique could be impacted by modern soil erosion, it would be in a location with steep slopes turned bare by bulldozers plowing a big subdivision.

Figure 4 presents our conceptual model for the experiment. In this idealized catchment, natural land cover occupies the upper-subcatchment and urban land cover occupies the lower-subcatchment. When the other controls on CADRs are the same for these two catchments (e.g., geology, no mass wasting), only land cover is the variable that might impact CADRs. We sampled an ideal catchment on a desert piedmont for this experiment in March of 2016, and we collected sediment samples from the main wash (CAPC01), from an upper-subcatchment where the city of Phoenix has a Sonoran Preserve (CAPC02), and from a lower sub-
catchment with active clearing of land for a subdivision (CAPC03). The major rock type in this catchment is consistently Early Proterozoic Metavolcanic Rocks. Therefore, we can exclude the impact of rock type on CADRs. Figure 5 provides insight about the surface condition of the sampling locations.

**Figure 4.** Conceptual model of a controlled experiment to determine if the CADR is influenced by urban construction in the Phoenix area. N refers to natural land cover and U refers to urban land cover. The sediment sample collected from the upper-subcatchment (CAPC02) represents the CADR of a nature preserve setting, while the sediment sample collected from the lower-subcatchment (CAPC03) represents the CADR impacted by a highly disturbed catchment that was experiencing ongoing suburbanization through the creation of a subdivision.

**Figure 5.** Study sites of the experiment to assess if the CADR is impacted by urbanization. (A) Google Earth view showing sampling locations and different land uses in the controlled experiment catchment. (B) Sampling location of the CAPC01 sample. (C) Sampling location of the CAPC02 sample. The CAPC02 subcatchment is within the Sonoran Preserve. (D) Sampling location of the CAPC03 sample, where the land surrounding CAPC03 was either recently built homes or bare ground.
3.2. Natural Background Sediment Yield Derived from $^{10}$Be

We collected samples of active-channel sediment from each of the 18 studied catchments that experienced LULCCs in the last two decades [33] to measure CADRs on the Sonoran Desert piedmont (Figures 2 and 3). All of the drainage networks in these 18 Phoenix-region catchments combine into a single channel that transfers sediment to the stock pond. CADR samples were all collected from this single channel just above each stock pond.

After sieving the collected fluvial sediments, just the 250–750 μm size fraction was chemically treated [58] at the Geochronology Laboratory at Korea University, Seoul, Korea. The treatment repeatedly etches minerals in a dilute HF/HNO₃ mixture [58]. We added a $^9$Be carrier with a $^{10}$Be/$^9$Be ratio < 3.0 × 10⁻¹⁵, then separated and purified the Be by ion exchange chromatography and selective precipitation of BeOH at pH > 7. BeOH was oxidized by ignition in a quartz crucible at 800 °C for 10 min [59]. BeO was then mixed with Nb metal and loaded onto targets for the measurement of the $^{10}$Be/$^9$Be ratio by the 6MV accelerator mass spectrometer (AMS) at the facility of the Korean Institute of Science and Technology (KIST), Seoul, Korea [59]. Isotope ratios were normalized to the $^{10}$Be standards [60], and the measured isotope ratios were converted to cosmogenic $^{10}$Be concentrations in quartz using the total $^{10}$Be in the samples and sample weights.

We calculated the CADRs using the CRONUS online calculator (version 2.2) [61], which calculates the $^9$Be production rate by integrating shielding conditions and latitude–altitude production rate functions [62–65]. CADR erosion rate calculations assume a bedrock bulk density of 2.7 g cm⁻³. In order to calculate the background-area-specific sediment yield represented by mass per unit area per time, we converted the CADR measured as length per time into the same unit of area-specific sediment yield (Mg km⁻² yr⁻¹) using a bedrock density of 2.7 g cm⁻³. Specifically, the background-area-specific sediment yield (SSY) was calculated using the following equation:

$$\text{Background SSY} = \text{CADR} \times \varrho$$  \hspace{1cm} (1)

where SSY is Mg km⁻² yr⁻¹, CADR is m Myr⁻¹ (= 10⁻⁷ km 10⁶ yr⁻¹), and $\varrho$ is g cm⁻³ (= 10⁻⁶ Mg 10⁻¹⁵ km³). An example of the conversion follows for the Cigar site: the background SSY is calculated as 7.1 m Myr⁻¹ × 2.7 g cm⁻³.

3.3. Correlation between Geomorphic Catchment Properties and Background Erosion Rate

We gathered quantitative and qualitative data for each of the selected catchments to determine if there were statistically significant correlations between a catchment property and natural background rates of erosion from the CADR. The morphological variables, such as drainage area, mean slope, and maximum relief, were generated by ArcGIS software using a 10 m DEM. Data on rock type were extracted from the geologic map provided by USGS (https://mrdata.usgs.gov/geology/state/state.php?state=AZ, accessed on 8 April 2021). Mean annual precipitation (MAP) and rainfall intensity were calculated using the precipitation data from various rain gauges of the Maricopa County Flood Control District (http://alert.fcd.maricopa.gov/showrpts_mc.html, accessed on 8 April 2021). In the semiarid watershed of southern Arizona, the sediment transport is generated when the rainfall intensity is greater than 10 mm for 30 min (I₃₀) [66]. Therefore, rainfall intensity was calculated based on the I₃₀. In addition, the 10-year average MAP and I₃₀ (Period 1: 1989–1999; Period 2: 2000–2009) are presented to reduce the effect of short-term variances in rainfalls. Jeong and Dorn [33] present detailed information on the various catchment properties analyzed here.

We excluded two of our observed natural background sediment yields from the bivariate correlation tests. These two watersheds had comparatively steep catchment mean slopes (6.6° and 6.2°) because the residential development backed up against mountain desert slopes. Generally, in Phoenix, residential development rarely occurs on this steep-slope terrain, because
of the abundance of alluvial fans and pediments with lower slopes. Because these two watersheds are influenced strongly by the presence of backing desert mountains, we omitted them from the correlation analysis in order to avoid bias.

Since rock types are not ordinal data, we completed analyses of Student’s t-tests to understand the importance of rock type on natural background sediment yield. Half of the stock pond watersheds are underlain by only granitic lithologies, ranging from granite to granodiorite with some diorite; the other half of the stock pond watersheds are underlain by a mix of rock types, typically including rhyolitic tuff (ignimbrite), basalt, metavolcanic, and metasedimentary rocks (Figure 3).

3.4. Modern Sediment Yield

The premise of this paper rests in comparing natural rates of erosion (CADRs) to prior research that analyzed two decades of historic erosion associated with LULCCs. This section summarizes the approach used to collect those historic erosion data presented in Jeong and Dorn [33].

Sediments collected from 18 stock ponds monitored soil erosion as the Phoenix urban fringe expanded between 1989 and 2013 [33]. A Supplementary Google Earth File linked with the main paper submission presents the 18 studied stock pond watersheds. The selection of the stock ponds to monitor was based on obtaining local information that a land-use change was planned from the prior use of cattle grazing. Sometimes, that land-use change did not occur or did not take place on the anticipated timescale. The result is a mixture of land-use changes impacting sediment yields as the Phoenix metropolitan area expanded (Figure 6). We stress that these areas are not susceptible to gullying or streambed erosion processes, and that sediment derives from mobilization of gravel and finer sediment by rainsplash and overland flow processes that sometimes involve rilling up to 5 cm in depth.

In each stock tank, nine 0.3 m segments of steel rebar were pounded flush to the surface of the sediment accumulation area in a 3 × 3 grid to account for spatial variability in sedimentation. Stock ponds were revisited at each major land use change to measure sediment accumulation depths on top of the rebar, located using a metal detector. Bulk density samples were collected from three points at each monitoring event and determined using the hydrometer method with the reported error term from the standard deviation. We estimated the maximum erosion rate with assumptions that all of the silt and clay derived from the local watershed, whereas the minimum erosion rate assumes that all of the silt and clay derived from aeolian deposition.

3.5. Comparison between Modern Sediment Yield and CADR

Most geomorphologists utilizing cosmogenic nuclides think about CADRs or natural rates of erosion in terms of millimeters per thousand years. Thus, the unit of CADR is different than soil erosion measurements, whether the audience involves scientists or policy-makers [67–69]. A key issue that needs to be resolved is to decide the most widely applicable unit to measure the sediment yield that results from soil erosion. Thus, the purpose of this section rests in clarifying our decision to present all sediment yield data in terms of area-specific sediment yield (Mg km⁻² yr⁻¹).

In general, sediment yield represents the amount of sediment that has been transported from one location to another measured as mass per time or volume per time or mass per unit area per time. The exact definition, however, can vary from country to country, among governmental agencies, and among different researchers (Table 1 (1-1)).

Table 1 (1-2) illustrates how soil erosion or sediment yield models vary in their data presentation. Universal Soil Loss Equation (USLE)-type models (USLE, RUSLE, and MUSLE) were designed to predict soil erosion on either plot scale or catchment scale, so they use the term average annual soil loss as represented by mass per unit area per time, which is often incorporated into other sediment yield models. Sediment yield models (SWAT, AGNPS, and WEPP) differentiate soil erosion and sediment yield by adding a sediment delivery ratio term
into their model. These models report the sediment yield result as either mass per time or mass per unit area per time (Table 1 (1-2)). Although the output of USLE-type models is different from other sediment models, cross-comparisons exist between USLE-type models and other sediment models [70,71].

Natural background rates use the CADR approach, and this scholarship takes two approaches (Table 1 (1-3)). One strategy converts modern area-specific sediment yield (Mg km\(^{-2}\) yr\(^{-1}\)) to a CADR (m Myr\(^{-1}\)) by dividing bedrock density (2.6–2.7 g cm\(^{-3}\)) [72,73]. Another CADR approach calculates background-area-specific sediment yield by multiplying bedrock density and then comparing it to modern sediment yield correcting for sediment bulk density (1.1 g cm\(^{-3}\)) [71,74,75] (Table 1 (1-3)). We adopted the latter to compare natural background and modern sediment yield data.

Figure 6. Historic aerial photography showing the typical land-use changes in four stock pond watersheds. The ID numbers correspond with the numbers in the figures and tables of this paper.
### Table 1. Different approaches to reporting sediment yield.

| Agency | Reported term | Unit | Reference |
|--------|---------------|------|-----------|
| Food and Agriculture Organization of the United Nations | Annual sediment yield | [M L⁻² T⁻¹](t km⁻² yr⁻¹) | FAO [76] |
| U.S. Department of the Interior, Bureau of Reclamation | Sediment yield | [M T⁻¹], [L³ T⁻¹](tons⁻¹ yr⁻¹), (m³ yr⁻¹) | USBR [77] |
| U.S. Department of the Interior, Bureau of Reclamation | Sediment yield rate | [M L⁻² T⁻¹], [L³ L⁻² T⁻¹](m³ km⁻² yr⁻¹) (ac ft mi⁻² yr⁻¹) | Strand and Pemberton [78]; USDA [79] |
| U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) | Sediment yield | [M T⁻¹] (tons yr⁻¹) | Wischmeier and Smith [80] |
| EUROPEAN SOIL DATA CENTRE (ESDAC) | Sediment yield | [M T⁻¹] (Pg yr⁻¹) | Borrelli et al. [81] |
| EUROPEAN SOIL DATA CENTRE (ESDAC) | Area-specific sediment yield | [M L⁻² T⁻¹], (Mg ha⁻¹ yr⁻¹) | Borrelli et al. [81] |

### 1 (1-2). Soil erosion and sediment yield models

| Model Name | Reported term | Unit | Reference |
|------------|---------------|------|-----------|
| Universal Soil Loss Equation (USLE), Revised Universal Soil Loss Equation (RUSLE) | Average annual soil loss | [M L⁻² T⁻¹], (tons acre⁻¹ yr⁻¹) | Wischmeier and Smith [80,82] |
| Soil and Water Assessment Tool (SWAT) | Sediment yield | [M L⁻²], (t ha⁻¹) | Arnold et al. [83] |
| AGRicultural Non-Point Source Pollution Model (AGNPS) | Eroded sediments | [M L⁻²], (tons acre⁻¹) | Young et al. [84] |
| Water Erosion Prediction Project (WEPP) | Average annual soil loss | [M L⁻² T⁻¹], (ton acre⁻¹ yr⁻¹) | Laflen et al. [85] |

### 1 (1-3). CADR scholarship comparing the CADR-derived background rate (time scale: 10⁸–10⁹) to the modern rate (time scale: 10⁶–10⁷)

| Approach | Background rate | Modern rate | Unit | References |
|----------|----------------|-------------|------|------------|
| 1. Convert the modern area-specific sediment yield (SSY) to the erosion rate using bedrock density (2.6–2.7 g cm⁻³) | Catchment averaged denudation rate (CADR) | Erosion rate (Area-specific sediment yield / Bedrock density (2.6–2.7 g cm⁻³)) | [L T⁻¹], (m Myr⁻¹) | Schaller et al. [72]; Bierman et al. [73] |
| 2. Convert the CADR to the SSY using bedrock density (2.6–2.7 g cm⁻³) | Area-specific sediment yield (CADR bedrock density (2.6–2.7 g cm⁻³)) | Area-specific sediment yield calculated using sediment density (1.x g cm⁻³) | [M L⁻² T⁻¹], (Mg km⁻² yr⁻¹) (kg m⁻² yr⁻¹) | Hewawasam et al. [74] a Clapp et al. [75] b Gellis et al. [86] c This study |

a Did not refer “density” to calculate the modern sediment yield, but described modern sediment as deriving from river gauge and reservoir measurements. b used sediment density: 1.6 g cm⁻³. c only mentioned that they used sediment density to calculate the sediment yield.
4. Results

The results section first reveals that aggressive urbanization processes in the Sonoran Desert do not appear to influence CADR measurements. This is followed by our CADR findings of natural background erosion rates for the 18 stock pond catchments, as well as the results of a correlation analysis comparing the CADR to various properties of the catchments. The third section then turns to a comparison between CADRs and modern rates of erosion to quantify the acceleration of erosion above the natural background by different LULCCs.

4.1. Influences of Recent Disturbances on CADRs

Although anthropogenic disturbances changed the surface condition and accelerated historical erosion in the Sonoran Desert [33], the influence of housing development on the \(^{10}\text{Be}\) CADR is below the limit that we can detect, resting at <10% in central Arizona—within in the external error range (Table 2), which follows the same pattern as in other global locations [56,57]. This finding suggests that \(^{10}\text{Be}\) CADR can represent natural background rates of erosion and can be used as a baseline for comparison with human-impacted erosion. Future researchers should be aware that our conclusion would not apply if the scale of anthropogenic erosion “mines” minerals below the cosmic ray penetration depth of ~60 cm.

Table 2. Catchment averaged denudation rates (CADRs) in the controlled experiment based on cosmogenic \(^{10}\text{Be}\) analyses. Sample ID number corresponds to the sampling locations that are presented in Figure 4. The CAP02 sample comes from the preserve, while CAP03 comes from the subdivision. The CAP03 sample integrates a larger drainage area that mixes preserve and development land uses.

| Sample ID | Latitude (°N) | Longitude (°W) | Elevation (m asl) | Production Rate (atoms g\(^{-1}\) yr\(^{-1}\)) | Blank-Corrected \(^{10}\text{Be}\) \(\pm 1\sigma\) (10\(^5\) atoms g\(^{-1}\)) | \(^{10}\text{Be}\) Erosion Rate \(\pm 1\sigma\) (m Myr\(^{-1}\)) | \(^{10}\text{Be}\) Sediment Yield \(\pm 1\sigma\) (Mg km\(^{-2}\) yr\(^{-1}\)) | Timescale \(\pm 1\sigma\) (kyr) |
|-----------|---------------|----------------|------------------|---------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| CAPC01    | 33.7494       | 112.1136       | 489              | 5.81                                        | 3.04 \(\pm 0.04\)                              | 11.0 \(\pm 0.1\)                                | 29.8 \(\pm 0.3\)                               | 53.7 \(\pm 0.6\)                              |
| CAPC02    | 33.7512       | 112.0984       | 527              | 5.92                                        | 2.37 \(\pm 0.03\)                              | 14.5 \(\pm 0.2\)                                | 39.2 \(\pm 0.5\)                               | 40.8 \(\pm 0.5\)                              |
| CAPC03    | 33.7526       | 112.01078      | 508              | 5.87                                        | 2.42 \(\pm 0.03\)                              | 14.1 \(\pm 0.2\)                                | 38.1 \(\pm 0.5\)                               | 42.0 \(\pm 0.5\)                              |

- a Total catchment averaged production rates were calculated using the CRONUS calculator (v 2.2) [61], which includes spallogenic and muogenic production. The reference production rate for sea-level and high latitude is 4.49 atoms g\(^{-1}\) yr\(^{-1}\) [63]. b Normalized with standard 07KNSTD and corrected for process blank. Error propagation was based on Balco et al. [61]. A large value between the internal error and the external error was selected. c Background sediment yield was calculated using Equation (1). d Beryllium-10 erosion rates were calculated using the CRONUS calculator (v 2.2) [61], assuming a bedrock density \(\rho = 2.7\) g cm\(^{-3}\). e Timescale of the catchment averaged denudation rate was calculated by dividing the \(^{10}\text{Be}\) concentration by the total production rate, which accounts for the duration over which a depth of \(z^* = \lambda/\rho \sim 60\) cm surface in the eroded basin.

4.2. Cosmogenic Nuclide \(^{10}\text{Be}-\text{Derived CADR}

Table 3 provides CADRs of each stock pond watershed (see Figure 2 for the location of each stock pond watershed). Table 3 presents details of each site needed to calculate production rates, the AMS measurement of the \(^{10}\text{Be}\) concentration, the calculation of the CADR in meters per million years, the residence timescale of the sediment in each catchment in thousands of years, and the calculation of natural background sediment yields.

A correlation matrix presents Pearson’s correlation coefficients between the natural background sediment yield and morphometric properties of each catchment (Table 4). Natural background sediment yield was significantly and positively correlated with mean slope \((r = 0.75, p < 0.05)\) and mean elevation \((r = 0.63, p < 0.05)\), but drainage area, relief, and drainage density did not show a clear correlation. Mean slope and mean elevation are significantly and positively correlated \((r = 0.8, p < 0.05)\).

Catchments with granitic rocks have higher rates of erosion than catchments that have a mixture of rock types (e.g., metamorphic, basalt, rhyolite, and granitic). This result was verified by a t-test comparing natural background sediment yields of granitic versus...
other rock types; the t-test result is statistically significant at $p < 0.05$ (Table 5). This difference is shown graphically in Figure 7. However, there is a problem with this simple statistical test in that rock type and mean slope are very much related. The granitic rock types occur in steeper catchments, while the non-granitic types have lower slopes; the reason for this is due to the geomorphic history of the region and not due to rock type [87].

We confirmed the correlation between rock type and catchment slope by using a t-test to compare the mean slope of granitic versus other rock types, where our null hypothesis was that there would be no difference in slopes between different rock types. We rejected this hypothesis of no difference after finding a statistically significant difference for granite ($M = 1.76, SD = 0.46$) versus other rock type ($M = 0.98, SD = 0.6$) conditions, $t(13) = 2.91, p < 0.05$ (Table 5). This difference is shown graphically in Figure 7B.

### Table 3. CADRs based on cosmogenic $^{10}$Be analyses. The sample ID corresponds to the different watersheds in the Phoenix Metropolitan Region (PMR) that are presented in Figure 2.

| Sample ID | Latitude | Longitude | Mean Long. | Elevation (m asl) | Avg. Basin slope ($^\circ$) | Blank-Corrected $^{10}$Be | $^{10}$Be Erosion Rate ± $^{10}$Be Sediment Yield ± Timescale |
|-----------|----------|-----------|------------|------------------|--------------------------|--------------------------|-------------------------------------------------|
| Cigar     | 33.685   | 112.534   | 33.726     | 112.547          | 0.4 ± 0.06               | 3.85 ± 0.06              | 7.1 ± 0.6                                    |
| Saguaro   | 33.801   | 112.204   | 33.816     | 112.197          | 0.7 ± 0.05               | 3.74 ± 0.05              | 12.1 ± 0.9                                   |
| Cline     | 33.856   | 112.149   | 33.867     | 112.152          | 1.2 ± 0.08               | 6.46 ± 0.07              | 6.9 ± 0.6                                    |
| Anthem    | 33.851   | 112.102   | 33.870     | 112.117          | 6.2 ± 0.04               | 2.62 ± 0.00              | 19.4 ± 1.4                                   |
| 5. Anthem | 33.852   | 112.100   | 33.857     | 112.097          | 1.8 ± 0.03               | 1.89 ± 0.03              | 27.0 ± 1.9                                   |
| Pepe      | 33.786   | 112.160   | 33.792     | 112.150          | 0.6 ± 0.06               | 5.19 ± 0.06              | 8.4 ± 0.6                                    |
| Bronco    | 33.775   | 112.117   | 33.783     | 112.117          | 0.6 ± 0.05               | 4.17 ± 0.05              | 10.7 ± 0.8                                   |
| Circle    | 33.771   | 112.061   | 33.772     | 112.062          | 6.5 ± 0.22               | 2.61 ± 0.06              | 18.5 ± 1.4                                   |
| Charlie   | 33.774   | 111.949   | 33.778     | 111.931          | 1.2 ± 0.06               | 1.89 ± 0.03              | 29.6 ± 2.1                                   |
| Rock      | 33.760   | 111.877   | 33.762     | 111.868          | 2.6 ± 0.07               | 1.29 ± 0.02              | 45.4 ± 4.0                                   |
| Creek     | 33.822   | 111.860   | 33.824     | 111.857          | 1.9 ± 0.08               | 7.92 ± 0.59              | 9.2 ± 0.7                                    |
| Buckhorn  | 33.772   | 111.727   | 33.787     | 111.760          | 1.5 ± 0.04               | 2.62 ± 0.00              | 21.0 ± 1.5                                   |
| The Rocks | 33.736   | 111.841   | 33.744     | 111.835          | 2.2 ± 0.03               | 1.38 ± 0.03              | 43.9 ± 3.1                                   |
| 12th St   | 33.720   | 111.806   | 33.718     | 111.814          | 1.7 ± 0.03               | 1.25 ± 0.03              | 48.2 ± 3.4                                   |
| 12th St   | 33.716   | 111.791   | 33.715     | 111.798          | 1.7 ± 0.03               | 1.35 ± 0.03              | 43.7 ± 3.2                                   |
| Asher Hills| 33.730  | 111.705   | 33.727     | 111.747          | 1.3 ± 0.04               | 2.63 ± 0.04              | 19.9 ± 1.4                                   |
| Gold Cyn  | 33.368   | 111.515   | 33.373     | 111.498          | 0.6 ± 0.05               | 3.33 ± 0.05              | 13.8 ± 1.0                                   |
| Peralta   | 33.335   | 111.430   | 33.345     | 111.417          | 2.0 ± 0.03               | 1.34 ± 0.03              | 38.7 ± 2.7                                   |

* Basin metrics used as input for calculating erosion rates using the CRONUS erosion rate calculator (v 2.2) [61]. Total catchment averaged production rates were calculated using the CRONUS calculator (v 2.2) [61], which includes spallogenic and muogenic production. The reference production rate for sea-level and high altitude is $4.49$ atoms g$^{-1}$ yr$^{-1}$ [63]. Normalized with standard 07KNSTD and corrected for process blank. Error propagation was based on Balco et al. [61]. A large value between the internal error and the external error was selected. Timescale of the catchment averaged denudation rate was calculated by dividing the $^{10}$Be concentration by the total production rate, which accounts for the duration over which a depth of $z^*$ = $\lambda / q$ = 60 cm surface in the eroded basin.

### Table 4. Correlation matrix between CADRs and key stock tank catchment variables.

| CADR | Mean Slope | Mean Elevation | Relief | Drainage Area | Drainage Density |
|------|------------|----------------|--------|---------------|-----------------|
| CDR  | 1          | 0.75 **        | 1      | 0.63 **       | 0.25            |
| Mean slope | 0.09       | 0.2            | 0.29   | 0.44          | 1               |
| Mean elevation | -0.25      | -0.31          | -0.19  | 0.44          | 1               |
| Relief | 0.34       | 0.25           | 0.42   | -0.2          | -0.49 *         |
| Drainage area | -0.49 *   | 1              |        |              |                 |

Note: $n = 16$, * Significant at $p < 0.1$, ** Significant at $p < 0.05$. 

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Table 5. Student’s t-tests results for rock types.

|                      | 1. CADR               | 2. Mean Slope          |
|----------------------|-----------------------|------------------------|
|                      | Granitic  | Non-Granitic | Granitic  | Non-Granitic |
| Mean                 | 88.06    | 42.13        | 1.76      | 0.98         |
| Variance             | 1567.79  | 941.61       | 0.21      | 0.36         |
| Observations         | 8        | 8            | 8         | 8            |
| Hypothesized Mean Difference |          |              |           |              |
| df                   | 13       | 13           |           |              |
| t Stat               | 2.59     | 2.91         |           |              |
| P(T ≤ t) one-tail    | 0.011    | 0.006        |           |              |
| t Critical one-tail  | 1.77     | 1.77         |           |              |
| P(T ≤ t) two-tail    | 0.022    | 0.012        |           |              |
| t Critical two-tail  | 2.16     | 2.16         |           |              |

Figure 7. Box and whisker plots comparing granite and other rock types for CADR and mean slope. 
(A) Box and whisker plots to compare the CADR of granite and other rock types. (B) Box and whisker plots to compare the mean slope of granite and other rock types. Boxes range from the 25th to 75th percentiles. Whiskers represent the data range. Red lines are medians.

4.3. Acceleration of Erosion by Different Land Uses

The desert pediments and alluvial fans of the study region (Figures 2 and 3) show a significant sensitivity to soil erosion from an anthropogenic disturbance [33]. Figure 8 takes data presented in Table 6, monitoring soil erosion over two decades, and places them in a ratio over CADR data presented in Table 3. Note that the conventions for units of erosion differ in the cosmogenic nuclide CADR literature and soil erosion scholarship (Table 1). CADRs are presented in terms of meters per million years, and Table 3 makes the conversion to the specific sediment yield more commonly used in soil erosion studies (see Tables 1 (1-3)).

The last two columns in Table 6 are data used to construct Figure 8. The labels in Table 6 of “minimum acceleration” and “maximum acceleration” relate to uncertainty over the source of silts and clays measured by Jeong and Dorn [33], who could not determine whether these came from weathering of rocks in the catchment or were blown in as desert dust. Thus, the “maximum” assumes that all of the accumulated sediment derived from erosion of catchment soils, whereas the “minimum” assumes that only the fine sand and larger size fractions are due to catchment erosion. Thus, the two graphs in Figure 8 depend on the assumption that the fines (silt and clay) that were deposited in the stock ponds were either all blown in or were sourced by weathering in the catchment.

The order of land use presented in Figure 8 reflects the typical change over time as the Phoenix metropolitan region expanded. The first period always involves cattle grazing. We were surprised that not all catchments experienced an acceleration above natural background.
rates from grazing. For those catchments experiencing an increase in erosion rate above the natural background due to grazing, the highest acceleration was 2.3–2.6 times.

Several catchments were burned by wildfire (Table 6). The designation “Fire1” in Table 6 is the period immediately after the fire, and Fire2 reflects a lower rate of erosion as vegetation grew back; Table 6 details the time periods of post-fire measurements. Immediately after the wildfire, sediment yields increased up to 9.7–10.4 times higher with a median increase of 2.9–3.2 times. After some vegetation grew back, the acceleration was less-up to 4.2–4.5 times higher with a median increase of 1.3–1.4 times.

Construction of subdivisions, commercial property, and infrastructure such as water tanks involves the exposure of bare ground. The “construction” category in Figure 8 lumps all these together. Construction increased sediment yields up to 5.0–5.6 times higher with a median increase of 2.9–3.3 times.

We continued our monitoring after construction and after the sealing of surfaces with concrete, asphalt, buildings, and landscaping. The sealing of urban surfaces led to one-tenth to one-half of sediment yields compared with natural background rates.

![Figure 8](image.png)

**Figure 8.** A comparison of the acceleration of specific sediment yields above natural backgrounds by different land uses in the Phoenix metropolitan area. The ratio was constructed from: (A) the minimum area-specific sediment yield calculated with the assumption that all fines are blown in divided by the CADR (i.e., the minimum acceleration in Table 6); and (B) the maximum area-specific sediment yield calculated with the assumption that all fines are from catchment weathering divided by the CADR (i.e., the maximum acceleration in Table 6).
### Table 6. Data on the stock tank catchments needed to calculate soil erosion, along with other watershed characteristics used in modeling soil erosion for the Phoenix metropolitan region (PMR). The last two columns (maximum and minimum acceleration) are a ratio of modern SSY to background SSY (from Table 3).

| Sample ID | Time Period | Field Description of Dominant Land Use | Land Use | Different Rock Types | MAP (mm) | Ad | At | Modern SSY ± 1σ | Modern SSY Background SSY ± 1σ | Minimum Acceleration | Maximum Acceleration |
|-----------|-------------|----------------------------------------|----------|----------------------|----------|----|----|----------------|-----------------------------|----------------------|----------------------|
| 1. Cigar  | 1990–2004   | grazing                                | C        | metamorphic, basalt,  | 207(20.9) 170(15.4) 2.6 6000 | 77.3 ± 3.8 89.2 ± 9.7 19.3 ± 1.5 | 4.0 | 0.0 4.6 | | | |
|           | 2005–2009   | grazing and off-road vehicle use       | C        | basalt, granite       |           | 89.6 ± 3.2 102.4 ± 9.8 | 4.6 | 0.0 5.3 | | | |
| 2. Saguaro| 1990–2004   | grazing                                | G        | metamorphic, basalt,  | 222(25.1) 184(14.1) 3.4 5800 | 41.4 ± 3.2 48.7 ± 7.6 32.7 ± 2.4 | 1.3 | 0.0 1.5 | | | |
|           | 2005–2009   | grazing & pipeline construction        | C        | basalt, granite       |           | 126.7 ± 4.6 143.2 ± 26.0 | 3.9 | 0.0 4.4 | | | |
| 3. Cline  | 1989–1995   | Some construction                      | C        | metamorphic, basalt,  | 222(25.1) 184(14.1) 3.4 9500 | 44.4 ± 5.4 52.0 ± 6.9 18.7 ± 1.5 | 2.4 | 0.0 2.8 | | | |
|           | 1996–2003   | commercial construction                | C        | basalt, granite       |           | 92.7 ± 3.1 103.7 ± 6.4 | 5.0 | 0.0 5.6 | | | |
|           | 2003–2004   | subdivision construction               | C        |                       |           | 160 ± 10.9 174.7 ± 25.4 | 8.6 | 0.0 9.4 | | | |
| 4. Anthem | 1989–1992   | after wildfire                         | G        | metavolcanic           | 222(25.1) 184(14.1) 0.88 3000 | 121.4 ± 15.8 136.7 ± 14.6 52.2 ± 3.8 | 2.3 | 0.0 2.6 | | | |
|           | 1993–1997   | after wildfire                         | F1       |                       |           | 309.3 ± 27.4 334.0 ± 25.4 | 5.9 | 0.0 6.4 | | | |
| 5. Anthem | 1989–1992   | after wildfire period 1                | F1       |                       |           | 254 ± 24.6 276.7 ± 45.8 | 3.5 | 0.0 3.8 | | | |
|           | 1996–1998   | after wildfire period 2                | F2       |                       |           | 308.6 ± 58.4 330.9 ± 32.8 | 4.2 | 0.0 4.5 | | | |
|           | 1999–2002   | after wildfire period 3                | F2       |                       |           | 146 ± 20.0 156.2 ± 14.9 | 2.0 | 0.0 2.1 | | | |
|           | 2002        | housing                                | C        |                       |           | 230.1 ± 12.8 255.7 ± 41.4 | 3.2 | 0.0 3.5 | | | |
|           | 2006–2008   | after subdivision built                | S        |                       |           | 12.9 ± 0.6 15.9 ± 4.0 | 0.2 | 0.0 0.2 | | | |
| 6. Pepe   | 1989–2008   | after subdivision and ongoing house construction | G | metavolcanic, basalt, granite | 222(22.8) 181(11.5) 0.99 3300 | 31.3 ± 3.7 38.4 ± 10.0 22.6 ± 1.7 | 1.4 | 0.0 1.7 | | | |
|           | 1999–2003   |                     | C        |                       |           | 112.5 ± 11.2 137.4 ± 32.4 | 3.9 | 0.0 4.8 | | | |
| 7. Bronco | 1989–1998   | after wildfire period 1                | F1       |                       |           | 254 ± 24.6 276.7 ± 45.8 | 3.5 | 0.0 3.8 | | | |
| 8. Circle | 1990–2010   | after wildfire period 2                | F2       |                       |           | 308.6 ± 58.4 330.9 ± 32.8 | 4.2 | 0.0 4.5 | | | |
| 9. Charlie| 1989–2004   |                       | C        |                       |           | 146 ± 20.0 156.2 ± 14.9 | 2.0 | 0.0 2.1 | | | |
| 10. Rock  | 1989–1992   | after wildfire period 1                | F1       |                       |           | 254 ± 24.6 276.7 ± 45.8 | 3.5 | 0.0 3.8 | | | |
|           | 1996–2003   | after wildfire period 2                | F2       |                       |           | 308.6 ± 58.4 330.9 ± 32.8 | 4.2 | 0.0 4.5 | | | |
|           | 2004–2009   | after wildfire period 3                | F2       |                       |           | 146 ± 20.0 156.2 ± 14.9 | 2.0 | 0.0 2.1 | | | |
| 11. Cave Creek | 1989–1992 | after wildfire period 1                | F1       |                       |           | 254 ± 24.6 276.7 ± 45.8 | 3.5 | 0.0 3.8 | | | |
|           | 1992–1999   | after wildfire period 2                | F2       |                       |           | 308.6 ± 58.4 330.9 ± 32.8 | 4.2 | 0.0 4.5 | | | |
|           | 2000–2003   | after subdivision built                | S        |                       |           | 12.9 ± 0.6 15.9 ± 4.0 | 0.2 | 0.0 0.2 | | | |
| 12. Buckhorn | 1989–1999 | after subdivision built                | C        |                       |           | 112.3 ± 4.9 128.5 ± 31.1 | 2.2 | 0.0 2.6 | | | |
| 13. The Rocks | 1989–1996 | after subdivision built                | C        |                       |           | 112.3 ± 4.9 128.5 ± 31.1 | 2.2 | 0.0 2.6 | | | |
| 14. 128th St | 1996–1998 | after subdivision built | S | | 15.8 ± 1.0 | 17.8 ± 4.6 | 0.1 | 0.2 |
| 15. 128th St 2 | 1989–1994 | grazing | G | granitic | 310(40.4) 248(28.0) 0.85 | 7000 | 94.7 ± 13.6 | 110.3 ± 27.1 | 130.1 ± 9.3 | 0.7 | 0.8 |
| 1995–2000 | after wildfire | F1 | | | 302.3 ± 10.8 | 342.0 ± 40.4 | 2.3 | 2.6 |
| 2001–2008 | road construction | C | | | 141.3 ± 7.4 | 159.9 ± 29.4 | 1.1 | 1.2 |
| 15. 128th St 2 | 1989–1994 | grazing | G | granitic | 310(40.4) 248(28.0) 0.31 | 2200 | 94.5 ± 12.4 | 109.5 ± 45.9 | 118.1 ± 8.6 | 0.8 | 0.9 |
| 1995–2000 | after wildfire | F1 | | | 250 ± 15.9 | 278.7 ± 94.4 | 2.1 | 2.4 |
| 2001–2008 | road construction | F2 | | | 135.7 ± 12.2 | 149.1 ± 48.4 | 1.1 | 1.3 |
| 16. AsherHills | 1989–2001 | grazing | C | granitic | 310(17.5) 248(18.4) 2.1 | 9800 | 125.9 ± 11.6 | 140.5 ± 27.6 | 53.8 ± 3.9 | 2.3 | 2.6 |
| 2002–2007 | house construction | C | | | 182.6 ± 7.9 | 199.1 ± 15.0 | 3.4 | 3.7 |
| 17. Gold Cyn | 1989–2009 | cattle grazing & house construction | C | ignimbrite, | 254(23.2) 209(17.9) 5.1 | 18000 | 45.3 ± 2.5 | 57.3 ± 13.1 | 37.3 ± 2.8 | 1.2 | 1.5 |
| 18. Peralta | 1989–2000 | grazing | G | ignimbrite, | 254(23.2) 209(17.9) 0.78 | 2800 | 44.7 ± 3.0 | 52.2 ± 3.8 | 104.6 ± 7.3 | 0.4 | 0.5 |
| 2001–2005 | subdivision construction | C | granitic, breccia | | 61.5 ± 3.9 | 77.4 ± 6.8 | 0.6 | 0.7 |
| 2006–2009 | after subdivision built | S | | | 6.2 ± 0.4 | 8.7 ± 2.8 | 0.1 | 0.1 |

**Note:** Abbreviations are as follows: MAP, mean annual precipitation during the 10-year period of study; P1, Period 1 (1989-1999); P2, Period 2 (2000-2009); I30, the total amount of rainfall that exceeded 10 mm for 30 min; Ad, drainage area; At, tank area; SSY, area-specific sediment yield. a Field description of the dominant land use reported by Jeong and Dorn [33]. b Dominant land use classified by this study. G, grazing; F1, immediately after a wildfire (typically 3–5 years); F2, after the F1 time period where some revegetation has occurred; C, construction in stock pond catchments; S, sealing by impervious materials. Land use land cover (LULC) was mainly classified using a LULC map supplemented by field observations and Google Earth satellite imagery. For example, some construction areas we monitored from the field were not classified in the LULC map. Then, using the Google Earth satellite imagery, we manually calculated the area of exposed bare ground due to construction activities when we could observe clear construction activities from the satellite imagery. c Minimum SSY in the unit of Mg (metric ton) km\(^{-2}\) yr\(^{-1}\), which was calculated assuming that all fines are blown in [33]. d Maximum SSY in the unit of Mg (metric ton) km\(^{-2}\) yr\(^{-1}\), which was calculated assuming that all fines are from catchment weathering [33].
5. Discussion

5.1. Soil Erosion in Arid Lands

Borrelli et al. [8] conducted an exhaustive and systematic review of soil erosion modeling, indicating that the greatest number of studies exist in temperate and Mediterranean zones with far fewer studies in arid lands. Perhaps the most detailed compilation of soil erosion in warm deserts comes from Vanmaercke et al. [88] who compiled Köppen-Geiger BWh data for Africa. More recent research by Vaezi et al. [40] revealed that slope steepness, vegetation cover, and soil erodibility factor have a statistically significant relationship with sediment yield in the northwest of Iran.

Figure 9 presents a plot of available data on BWh sediment yield, compiled by Jeong and Dorn [33], where arid data plot between African [88] and European [89] compilations for modern sediment yields. We also plot our CADR data for the 18 Phoenix-region watersheds in Figure 9, along with previously compiled [90] CADR data for arid regions—both tectonically active and tectonically inactive. Note that CADR data follow the same basic trend of increased area-specific sediment yield in smaller watersheds, but the relationship between CADR-SSY and drainage area is not statistically significant. We note that the median SSY for all CADR data is 71 Mg Km$^{-2}$ yr$^{-1}$, and this is about two-thirds of the modern median for the SSY at 110 Mg Km$^{-2}$ yr$^{-1}$ for BWh climates.

Figure 9. Comparison of the modern area-specific sediment yield in BWh climates (+ symbol) compiled by Jeong and Dorn [33] with pre-anthropogenic background sediment yields obtained by $^{10}$Be CADR measurements in this study (solid circles) and those compiled previously [90] for arid regions (solid squares).

Figure 10 compares our CADR data from the Sonoran Desert with other CADRs from arid and semi-arid watersheds compiled by Harel et al. [90]. We reclassified the global $^{10}$Be denudation rate compilation [90] into four different groups based on climate and seismic activity, and our Sonoran Desert background soil erosion data (Table 3) are similar to other tectonically inactive and arid watersheds.
Figure 10. Box plots comparing the $^{10}$Be denudation rates we observed in the tectonically inactive Sonoran Desert with a global-scale $^{10}$Be denudation analysis [90]. Inactive/arid regions have a seismicity < 2 categorized by Harel et al. [90] and a mean annual precipitation (MAP) of <250 mm. Inactive/semi-arid regions also have a seismicity < 2 categorized by Harel et al. [90] but a mean annual precipitation (MAP) of greater than 250 mm but less than 500 mm. Active/arid regions have a seismicity > 2 categorized by Harel et al. [90] and a mean annual precipitation (MAP) of <250 mm. Active/semi-arid regions also have a seismicity > 2 categorized by Harel et al. [90] but a mean annual precipitation (MAP) of > 250 mm but < 500 mm.

5.2. Grazing’s Acceleration of Erosion

Grazing has long been recognized as an important factor influencing soil erosion in arid lands [40,91–96]. Fourteen of the 18 Phoenix-area watersheds were monitored during the period when grazing was the predominant land use (Table 6). When we compared natural CADR erosion rates (Table 3) to the period of grazing in the same Sonoran Desert watershed, 6 of the 14 drainage basins did not experience an acceleration of erosion from grazing. The eight watersheds that did experience enhanced erosion compared with the natural background CADR had a minimum acceleration ranging from 1.3x to 4.0x.

In order to explain the unexpected finding of no acceleration in several of the watersheds, we can rule out a prehistoric anthropogenic effect, because the timescales of $^{10}$Be CADR results range from 16.4 ka and 101 ka (Table 3). This means that the analyzed quartz particles were exposed to cosmic ranges during the last glacial cycle. Although early humans arrived in the New World at the end of the Pleistocene [97], their effect on erosion would likely have been minimal because of the low population density in this region during the late Pleistocene and Holocene [98].
Another possible explanation as to why grazing did not accelerate erosion above natural backgrounds in six of the watersheds could be due to higher erosion rates in previous wetter climates [99,100] in the 16.4 ka to 101 ka timescale of $^{10}$Be exposure (Table 3). Yet another possible explanation would be differences in grazing histories between basins, in that it is possible that the six basins not experiencing an acceleration of erosion from grazing might have had minimal grazing during the time period of monitoring; unfortunately, different grazing histories is a possibility that cannot be evaluated because the only grazing record for the watersheds consists of a permit to graze cattle and not the number of cattle actually on the range in any given year.

5.3. Wildfire’s Acceleration of Erosion

Wildfire is widely recognized as an agent that accelerates erosion of soils [7,34,41,101,102]. This is true even in arid regions [103]. Wildfires occurred in 6 of the 18 studied watersheds after monitoring had started. That wildfires took place in one-third of the studied basins is a reflection of the encroachment of the urban boundary and the poor behavior of individuals on these lands, such as lighting cigarettes and letting off-road vehicles stand on tall dry grass.

Erosion after the wildfires was monitored immediately after the fire. Then, for watersheds that did not experience construction from urbanization, we continued to monitor erosion as the vegetation density gradually increased over time. Sediment yields immediately after a fire had median acceleration of 4.2–4.5x, with some watersheds accelerating at rates 10x above the natural background. Then, after a decade of revegetation, the median acceleration dropped to 1.3–1.4x the natural background erosion rates.

Our findings on the acceleration of erosion from wildfire detailed in Table 6 are the first known observations of how much wildfire can accelerate soil erosion in an arid region. Since wildfire did not occur naturally in the Sonoran Desert prior to the invasion of European grasses [50], we are confident that the CADR signal for natural erosion did not include wildfire. The lack of European grasses meant that we could also rule out prehistoric enhancements of erosion rates due to wildfire; our confidence in this interpretation is bolstered by previous observations that the Aboriginal Australian’s use of fire was not sufficiently intense or long lasting to alter CADR erosion rates [104].

5.4. Urbanization’s Acceleration of Erosion

Although the impact of urbanization processes on soil erosion had been studied previously (e.g., [105,106]), Russell et al. [22] produced the first comprehensive analysis of urbanization’s impact on sediment yields. Only 3 of the 18 studied Phoenix-region watersheds did not experience construction activities leading to houses, commercial properties, or other infrastructure such as water tanks. Since our watersheds lacked any gullyling, with the largest rills reaching 5 cm in depth, we interpret the impact of construction over the natural background to be the result of exposing bare ground to rainsplash and overland flow. The median acceleration of 2.9–3.3x with the higher end of acceleration being 5.0–5.6x is the first observation of its kind on just how much urbanization can increase soil erosion rates in arid settings. In addition, we obtained the first confirmation that sealing of urban surfaces with asphalt, concrete, buildings, and associated landscaping greatly reduces erosion well below natural rates of erosion—roughly 1/10 to 1/2 CADR measurements.

Some might think of the arid region as already having an abundance of bare ground exposure, and this is true. Jeong and Dorn [33] used historic photography to estimate the vegetation cover of these watersheds during periods of grazing, and coverage ranged from 4% to 37%. Our field observations of what happens during rain events in a grazed area as opposed to bare-ground are fully consistent with Cerdà [107], who showed that surface rock fragments slow down runoff to raise infiltration rates and decrease erosion rates. Construction removes the natural cover of cobbles that often form as a lag in the Sonoran Desert [108], which could be part of the explanation of urbanization’s acceleration of soil erosion.
The stakes associated with urbanization-enhanced soil erosion tend to be spatially variable, as is the case for all soil erosion [19,31,109]. For example, the effects of urban soil erosion in the Phoenix area are relatively minor—impacting such issues as reservoirs [110], water quality [111], and health effects from heavy metals [111]. In other cities, soil erosion can impact the urban poor in a variety of ways, including a negative health impact [112] and water quality [113]. Some value urban soils as vital for urban agriculture and a pathway towards sustainability [114]. Enhanced urban soil erosion might remove carbon stored in city soils [115,116], or it might end up in a setting where it can be more stable, such as a reservoir [117].

6. Conclusions

The concept of an Anthropocene epoch, starting with the onset of a significant human impact on the Earth, has been debated in soils [118] and geomorphological scholarship [119], with the hypothesis of a “great acceleration” [120] associated with anthropogenic activities. Here, for the first time, we place specific numbers on the acceleration of erosion above natural background rates in the Sonoran Desert of Arizona, United States from grazing, wildfires, and urbanization.

Knowing just how much grazing, wildfire, and urbanization can increase soil erosion above natural rates has implications for the sustainable management of arid-region soils. The accelerated soil erosion by human activities is a major concern for land management with respect to soil degradation (e.g., [11,12,15,19,22,36,121–124,125]). Through their extensive review of tolerable soil erosion rates for human society, Verheijen et al. [126] concluded that soil functions can generally be maintained as long as soil erosion does not exceed natural erosion rates. Thus, our framework for combining erosion monitoring and CADRs would allow land managers to have a better understanding of the quantitative target rate of erosion that can maintain good ecological status and halt or potentially reverse land degradation [127]. This research illustrates that a quantitative target of a natural background rate of erosion would be particularly useful when planning and managing different land uses such as vineyards [21,26,122,125,128], specific locations impacted by wildfire [33–35], and construction sites [22,24,33].

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