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American bison kill site use and abandonment amid drought and cultural shifts in late Holocene Montana

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Understanding how ecological and social constraints interacted to shape bison hunting systems during the late Holocene reveals the dynamic ways bison hunting strategies adapted to changing conditions. At the Bergstrom site in central Montana, bison were hunted intermittently for roughly seven centuries before archaeologically visible use ceased near 1100 cal yr BP. To explain why hunting stopped despite continued regional bison presence, we integrate archaeological excavation, radiocarbon chronology, and multiproxy riparian paleoecology (pollen, charcoal, coprophilous fungal spores) with regional drought reconstructions and analysis of radiocarbon-dated bison occurrences. Local environmental proxies show stable vegetation, low fire activity, and persistent large-herbivore indicators after abandonment, providing little support for ecological transformation as a cause. Regional synthesis reveals that archaeological bison frequencies increased 5.5-fold through the Holocene while paleontological frequencies remained stable, with peak hunting intensity coinciding with severe, multi-decadal droughts. These findings contradict models of population tracking and indicate that hunting reorganization, not prey scarcity, led to site abandonment. The most parsimonious explanation is convergence of constraints: drought reduced processing water at hydrologically marginal sites while rising organizational demands favored larger, infrastructure-intensive communal operations. The abandonment of the small Bergstrom site likely reflects an adaptive reorganization of bison hunting efforts toward larger, topographically advantageous sites better suited to increasingly coordinated communal hunting systems. This case study illustrates how historical hunting

systems maintained regional persistence through episodic site use and localized abandonment, providing empirical guidance for contemporary managers seeking to restore the spatial heterogeneity and adaptive capacity that supported bison-human systems under climatic variability.

KEYWORDS

bison hunting, paleoecology, drought, archaeology, Great Plains, human–environment systems, Holocene, resilience

Introduction

Understanding how bison and human hunters adapted to environmental variability over millennia provides critical context for contemporary bison management under climate change. The four sectors of the modern Bison Management System, including private production, public wildlife agencies, nonprofit conservation organizations, and Tribal nations, operate under distinct regulatory frameworks and resource constraints while sharing the challenge of sustaining bison populations amid increasing climate variability (Martin et al., 2021; Shamon et al., 2022). Conservation paleobiology offers a long-term perspective by revealing how bison–human systems responded to past episodes of drought and resource stress (Dietl and Flessa, 2011; Rick and Lockwood, 2013). Archaeological and paleontological records from the Northern Great Plains document millennia of system persistence through environmental conditions exceeding the range of modern instrumental records (Cook et al., 2007), providing important context for understanding adaptive capacity and vulnerability in coupled human–natural systems (Swetnam et al., 1999; Cooper, 2008; Breslawski, 2023).

Archaeological records from the Northern Great Plains document an intensification of bison hunting during the late Holocene (ca. 3000–250 cal yr BP), when many kill sites experienced episodic use and eventual abandonment despite continued regional bison presence and apparent ecological suitability (Reeves, 1990; Peck, 2011; Wendt et al., 2022). Comparable spatiotemporal patchiness has been documented for earlier Holocene adaptations across the Great Plains, where communities responded to mid-Holocene aridity through regionally divergent strategies (Breslawski, 2023). This pattern suggests that factors beyond prey availability structured changing hunting systems. Recent trans-Holocene analyses show that artiodactyl hunting broadly covaries with climatic seasonality, with summer temperature exerting a strong negative effect (Byers et al., 2024). Understanding what drove spatial and temporal heterogeneity in site use has important implications for modern bison management, where fixed boundaries and intensive management may limit the flexibility that is observed in archaeological systems.

The Bergstrom site (24JT0893) in central Montana provides a test case for examining these dynamics. Bison were hunted there

intermittently for approximately 700 years before archaeologically visible site use ceased near 1100 cal yr BP, a period when regional bison populations persisted and hunting activity intensified elsewhere. We ask, what drives variability in bison hunting intensity, and what determines which sites remain viable as hunting systems reorganize?

Bison populations and human hunters have coexisted in the Northern Great Plains since the Late Pleistocene (Frison et al., 1991; Kornfeld et al., 2016). During the late Holocene, hunting organization underwent intensification. Hunters shifted from dispersed, small-group intercepts characteristic of the Late Archaic (ca. 3000–1000 cal yr BP) to increasingly coordinated communal drives during the Late Prehistoric period (after ca. 1350 cal yr BP) at spatially concentrated locations with substantial infrastructure, including driveline complexes of monumental size (Brink, 2008; Bamforth, 2011; Zedeño et al., 2014; Lee et al., 2019). At sites such as Head-Smashed-In, Two Medicine Valley complexes, and Paradise Valley, hunters invested in drive lines, corrals, and jump complexes, coordinating labor to process large numbers of animals (Brink, 2008; Cooper, 2008; Bamforth, 2011; Zedeño et al., 2014; Kornfeld et al., 2016; Bethke et al., 2018; Lee et al., 2019). This transformation occurred after the hot and dry mid-Holocene, during a period of generally cooler and moister conditions (Grimm et al., 2011; Shuman and Marsicek, 2016) that was interrupted by severe droughts (Cook et al., 2007, 2010). Large communal operations concentrated effort at hydrologically and topographically favorable locales, increasing carcass throughput and processing efficiency but also dependence on specific resources including water, forage, and fuel. Environmental variability likely reinforced this differentiation. Locations with perennial water remained practical for large-scale hunts during droughts, while hydrologically marginal sites became untenable (Reeves, 1990; Cooper, 2008; Peck, 2011; Roos et al., 2018; Edmo, 2024).

We evaluate four non-exclusive hypotheses linking climate variability, ecological change, and hunting logistics:

- H0. Population tracking (null hypothesis). Hunting activity directly tracked bison population density through coupled responses to environmental conditions. *Mechanism:* Drought reduced local forage and water, decreasing bison

density; hunters tracked these fluctuations, abandoning sites during low-density periods and returning when conditions improve. *Predictions*: (1) Archaeological and paleontological bison occurrence covary positively through time; (2) archaeological gaps correspond to regional bison decline; (3) site reoccupation follows drought recovery.

- H1. Ecological transformation. Local environmental change persistently reduced the site's suitability for hunting. *Mechanism*: Directional shifts in vegetation, fire regime, or hydrology degraded habitat quality or processing capacity. *Prediction*: Pollen, charcoal, or herbivore proxies record, persistent shifts in vegetation structure, fire activity, or large herbivore presence during or after the final occupation (ca. 1100 cal yr BP).
- H2. Procurement reconfiguration. Regional shift toward large, infrastructure-intensive communal hunts altered site-selection criteria, making smaller sites less viable. *Mechanism*: As group sizes and processing demands increased, operations required more water, space, and labor coordination; small intercept sites failed to meet elevated operational thresholds. *Prediction*: Hunting ceases at small sites during the period of communal hunting expansion (post-2000 cal yr BP), even where local ecological conditions remain favorable; artifact assemblages at Bergstrom reflect small-scale, opportunistic use rather than large-scale communal operations.
- H3. Converging constraints. Multiple limiting factors simultaneously exceeded the site's adaptive capacity. *Mechanism*: Drought reduced processing water availability while rising organizational demands increased water and

space requirements; sites unable to meet both constraints became nonviable even if usable during other periods. *Prediction*: Final occupation coincides with onset of severe droughts; no reoccupation occurs despite regional bison persistence and subsequent drought alleviation; local ecological conditions remain stable, indicating constraints were operational rather than ecological.

H3 draws on resilience theory's observation that systems become especially vulnerable when multiple stresses interact to reduce flexibility (Holling, 1973; Holling and Meffe, 1996; Scheffer et al., 2001; Walker et al., 2004). We integrate archaeological excavation, radiocarbon chronology, and projectile-point typology with paleoecological records of vegetation, fire, and herbivore activity (pollen, macroscopic charcoal, and herbivore-indicator spores), regional drought reconstructions, and a synthesis of archaeological and paleontological bison occurrences to evaluate these hypotheses. Understanding which factors drove historical site abandonment, and the structural characteristics of long-persistent bison procurement systems, provides empirical guidance for contemporary managers navigating similar pressures under climate variability.

Setting

The Bergstrom site (46.734, -109.791; 1410 m elevation) is situated west of Garneill, Montana, on the north flank of Judith Gap, a low pass between the Little Belt Mountains to the west and the Big Snowy Mountains to the east (Figure 1). This pass forms a natural constriction through which bison herds would have likely

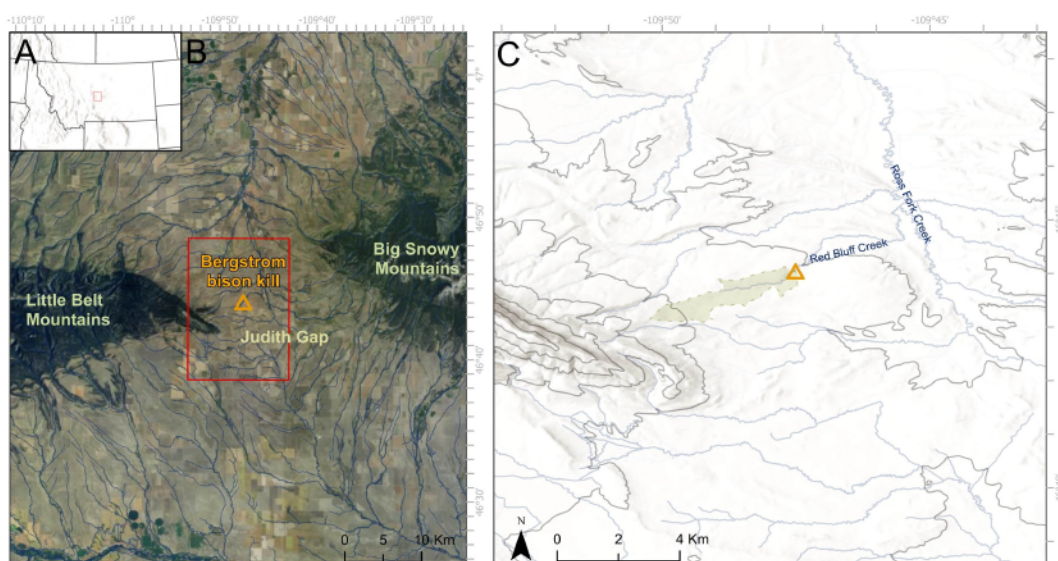


FIGURE 1

Map of the Bergstrom bison kill site and Red Bluff Creek in the Judith Gap, Montana, USA. (A) Location of the study area in the Northern Great Plains. (B) Regional context showing land cover with the Judith Gap between the Little Belt Mountains and Big Snowy Mountains. (C) Local topographic map of Red Bluff Creek; contour interval (gray line) is 100 m, and the shaded green area delineates the drainage feeding the RBC19 core site.

been directed. Archaeological materials are abundant in sediments on the southeastern slope above Red Bluff Creek, which originates from a spring on a descending spur of the Little Belts. The site, with open grasslands, water, and gently sloping terrain funneling through a landscape constriction, occupies a favorable landscape position for intercept hunting.

The surrounding matrix of present-day land use includes grasslands with native bunchgrasses (*Pseudoroegneria spicata*, *Festuca idahoensis*) and introduced crested wheatgrass (*Agropyron cristatum*), and agricultural fields including alfalfa (*Medicago sativa*), winter and spring wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and field pea (*Pisum sativum*). Slopes above the creek support mixed grass-shrub assemblages with Poaceae, *Symphoricarpos*, *Artemisia ludoviciana*, and flowering forbs including *Achillea millefolium*, *Primula*, and *Anemone*. The riparian vegetation community is dominated by grasses, rushes (Juncaceae) and sedges (Cyperaceae).

The Judith Gap weather station (2000–2016) located 7 km southeast of the Bergstrom site, records temperature averages of 14.6°C/−0.4°C (max/min) and 378 mm yr^{−1} precipitation, about half of which falls between May and July. Snow accumulation begins in late October, peaks in January, and typically clears by May.

Bison bone and side-notched projectile points are scattered across the northwest-facing slope above the creek. Nine archaeological excavation units on the southeast slopes of Red Bluff Creek and two sediment cores from the adjacent riparian zone provide the multiproxy record at the Bergstrom site.

Methods

Our investigation integrated archaeological excavation, sediment coring, and laboratory analyses to reconstruct past environmental conditions and human land use at the Bergstrom site and Red Bluff Creek across the period of documented bison hunting and subsequent abandonment.

Archaeological excavation

In spring 2019, we excavated nine 1 × 1 m units on a northwest-facing slope above Red Bluff Creek. Units were placed to capture cultural stratigraphy near a recent collector's pit that yielded a high concentration of bison bone, identified during the initial site survey. All units were hand-excavated at arbitrary 10 cm levels to culturally sterile sediment. Sediments were screened through 1/8" (3.2 mm) mesh, and diagnostic artifacts including lithic projectile points and bison bone were mapped *in situ*. Bulk sediment samples were collected from selected levels for radiocarbon analysis. Sediment characteristics were documented using Munsell color charts, field texture analysis, and structural observations. Photographs were taken at each level. Cultural features, bone concentrations, and artifact distributions were recorded using standard archaeological protocols.

Projectile point typologies provide general cultural affiliations, namely Besant and Avonlea (Wettlaufer and Moss, 1955; Kehoe and

McCorquodale, 1961), though we acknowledge the limitations in assigning precise group identities or behavioral profiles (Meyer and Walde, 2009). Quantitative faunal analysis (MNI, NISP, age/sex profiles) was not available for this initial investigation. However, the density of bison bone and projectile points within cultural strata, combined with typological and stratigraphic sequencing, is consistent with repeated kill-site use over several centuries.

Radiocarbon dating

Radiocarbon samples consisted of charred plant material selected from secure stratigraphic contexts. Samples were submitted to the NOSAMS facility at Woods Hole Oceanographic Institution for AMS dating. Radiocarbon ages were calibrated using the IntCal20 calibration curve (Reimer et al., 2020). All calibrated dates were reported in calendar years before present (cal yr BP) or converted to the Gregorian calendar (BCE/CE) where appropriate.

Sediment coring

Two sediment cores (RBC19 and RBC20) were collected from the saturated riparian zone of Red Bluff Creek, directly adjacent to the excavation area. Core RBC19 was retrieved in May 2019 using a Russian peat borer (6 cm diameter, 50 cm chamber) in overlapping drives to ensure stratigraphic continuity. Core RBC20 was collected in June 2020 using identical methods. Core RBC20 reached a depth of 240 cm and spans approximately 12,500 cal yr BP. The upper 115 cm of RBC19 covers the last ca. 2000 years and provided the focus for high-resolution paleoecological analysis corresponding to the period of archaeological site use.

Sediment core chronology

Chronological control for the composite core record is based on 11 AMS radiocarbon dates: 9 from RBC19 and 2 from RBC20. Age-depth modeling was conducted using rbacon 3.2.0 (Blaauw and Christen, 2011) in R 4.5.1 (R Core Team, 2025). The two cores were aligned stratigraphically based on overlapping organic transitions and consistent sediment texture across drives. Archaeological radiocarbon dates from the excavation unit located ca. 30 meters southeast from the sediment core are treated as independent of the core chronology and not integrated into the Bayesian age model.

Pollen analysis

Pollen analysis was used to reconstruct vegetation dynamics across the period of site use and abandonment. Sediment samples of 1 cm³ were extracted at intervals ranging from 2–14 cm, yielding a mean temporal resolution of 93 years (range: 14–507 years). Sample preparation followed standard palynological protocols (Bennett and Willis, 2001), with modifications to optimize recovery. Hydrofluoric

acid treatment was replaced by density separation using lithium heteropolytungstate (LST, density 2.0 g cm^{-3}), followed by centrifugation at 1800 rpm for 20 minutes, overnight settling, and decanting to remove mineral particles.

All samples were spiked with exotic *Lycopodium* spores to enable calculation of absolute pollen concentrations ($\text{grains cm}^{-3} \text{ yr}^{-1}$). Slides were mounted in silicone oil and examined at 400–1000× magnification. A minimum of 300 terrestrial pollen grains per sample were identified and counted. Terrestrial taxa were expressed as percentages of the total terrestrial pollen sum, and aquatic taxa were expressed as percentages of the total pollen sum. Cyperaceae was excluded from the terrestrial sum and treated as aquatic.

Pinus grains with intact distal membranes were classified to subgenus level: subg. *Strobus* (verrucate membrane) likely represents limber pine (*P. flexilis*) and whitebark pine (*P. albicaulis*), while subg. *Pinus* (psilate membrane) likely represents lodgepole pine (*P. contorta*) and ponderosa pine (*P. ponderosa*). Cupressaceae pollen was assigned to *Juniperus*-type, representing Rocky Mountain juniper (*J. scopulorum*), creeping juniper (*J. horizontalis*), and common juniper (*J. communis*) present in the region. To quantify vegetation openness, we calculated a functional group ratio as $\frac{\text{trees}}{\text{shrubs} + \text{grasses}}$, interpreted as a proxy for canopy cover (AP: NAP). Pollen diagrams were constructed using the *rioja* package (Juggins, 2020) in R.

Charcoal analysis

Macroscopic charcoal analysis provided a record of local fire activity throughout the period of interest. Contiguous 2 cm^3 sediment samples were collected at 1-cm intervals from core RBC19. Samples were disaggregated using a 1:1 solution of commercial bleach and 5% sodium hexametaphosphate (NaPO_3)₆ for 24 hours to oxidize organic matter and disperse clay particles. Charcoal fragments $\geq 125 \mu\text{m}$ were separated by wet sieving and counted under stereomicroscopy (Whitlock and Larsen, 2001).

CharAnalysis software (Higuera et al., 2009) was used to analyze charcoal counts. Charcoal concentrations (particles cm^{-3}) were converted to influx values (CHAR; $\text{particles cm}^{-2} \text{ yr}^{-1}$) using sedimentation rates derived from the age-depth model. Background charcoal (BCHAR) was calculated as a smoothed low-frequency component of the CHAR series, representing long-term trends in extralocal fire activity or baseline biomass burning.

Herbivore proxy analysis

To track the presence of large herbivores, we analyzed spores of a coprophilous fungus (*Sporormiella*) and a disturbance-indicator plant (*Selaginella densa*). *Sporormiella*-type spores, associated with herbivore dung (Burney et al., 2003; Davis and Shafer, 2006; Parker and Williams, 2012; Gill et al., 2013), were counted during routine pollen analysis and expressed as percentages of the total palynological sum. *Selaginella densa*-type spores, representing a mat-forming lycophyte tolerant of trampling and grazing

(Hubbard, 1951; Shay et al., 2001), were similarly quantified. These proxies have been used in Northern Great Plains and interior western environments to track large herbivore presence and pressure over millennial timescales (Davis and Shafer, 2006; Grimm et al., 2011).

Regional hydroclimate reconstruction

To assess regional hydroclimate variability and potential drought stress during the last two millennia, we analyzed summer Palmer Drought Severity Index (PDSI) reconstructions from the North American Drought Atlas (Cook et al., 2007, 2010). Grid point 100 (110.0°W, 45.0°N) lies approximately 100 km south of Red Bluff Creek and provides the closest available record that fully covers the period of interest.

For each drought event ($\text{PDSI} < -2.0$), we calculated duration (number of consecutive years), intensity (mean PSDI during the event), and an integrated drought magnitude index (duration $\times$ absolute intensity). These metrics were calculated for all events exceeding 5 years duration between 2000 cal yr BP and present.

Regional bison occurrence frequencies

To evaluate whether the local decline in hunting at Bergstrom reflects a broader pattern, we analyzed regional bison occurrence frequencies using the dataset and methods of Wendt et al. (2022), with data originally sourced from Neotoma Paleocology Database (Williams et al., 2018) and Canadian Archaeological Radiocarbon Database (Gajewski et al., 2011). We subset the database to radiocarbon-dated strata containing bison remains within 600 km of the site, distinguished archaeological and paleontological contexts ($n = 579$ archaeological, $n = 76$ paleontological), and consolidated overlapping date ranges (Supplementary Table S3). Occurrence frequencies were calculated using a standard taphonomic correction curve (Surovell et al., 2009).

To test whether archaeological hunting intensity tracks bison availability (H_0 : population tracking), we compared temporal patterns in archaeological versus paleontological occurrence frequencies. If hunting directly tracks prey presence, the ratio of archaeological to paleontological occurrences (A:P) should remain constant through time, with both frequencies covarying proportionally.

We calculated A:P ratios for major time periods: Pleistocene ($>11,700$ cal yr BP), early Holocene (11,700–8000 cal yr BP), mid-Holocene (8000–4000 cal yr BP), and late Holocene (4000–0 cal yr BP). Temporal variation in A:P ratios was tested using chi-square test of independence. We also evaluated whether archaeological or paleontological frequencies covary through time by binning occurrences into 100-year intervals and calculating Spearman's rank correlation between the resulting time series. Deviation from constant A:P ratios or lack of positive correlation would indicate that hunting intensity responds to factors beyond prey availability.

To assess site-level patterns in regional context, we calculated the mean A:P ratio during the period surrounding Bergstrom

abandonment (1500–800 cal yr BP) and compared it to the late Holocene baseline, expressed as standard deviations from the mean. Comparison of regional drought reconstructions, bison occurrence patterns, and site-specific proxy records situates the Bergstrom sequence within broader regional dynamics of climate variability and hunting intensity.

Results

Archaeological chronology and site use history

Excavation stratigraphy

Excavation of Unit 3 exposed a 55 cm stratigraphic sequence of six distinct cultural and depositional layers (Strata I–VI) (Figure 2). Dense bison bone, lithic projectile points, and charcoal lenses are concentrated in Strata III–VI, representing the main period of use. Stratum VI (deepest; 2.5YR 4/6 red clayey sand) yielded Besant projectile points, charcoal, and bone fragments. Stratum V (5YR 3/1 very dark gray clayey silt) contained bone fragments, charcoal, and Besant points. Strata III–IV (both 5YR 3/2–3/3 dark reddish brown clayey sand) produced Avonlea projectile points and the highest faunal densities. Stratum II (5YR 3/1 very dark gray coarse sand) contains bone fragments but not cultural material. The striking dark colors of Strata II and V (5YR 3/1) indicate intervals of soil

development under reduced sedimentation, comparable to buried mollic horizons that form over centuries of landscape stability in the Great Plains (Mandel, 2008; Mason et al., 2008; Woodburn et al., 2017).

Stratum I (10YR 2/2 very dark brown silty sediment) contrasts with cultural layers. Root penetration and sparse bone suggest post-use colluvial/alluvial deposition with limited pedogenesis. The lack of soil horizonation in Stratum I implies a short stability interval, plausibly less than a century, consistent with sediment derived from recent cultivation and hillslope erosion above the site.

Sharp contacts between cultural and post-use strata, a consistent color progression (red to dark reddish-brown/very dark gray to very dark brown), two buried dark surfaces, and the absence of cultural material in upper strata indicate a depositional hiatus during which soils formed, following burial of the archaeological deposits. Low-impact or ephemeral activities could have occurred below detection thresholds.

Radiocarbon chronology

Three AMS radiocarbon dates from Unit 3 constrain the interval of archaeologically visible use (Table 1). Stratum VI dates to 1707 cal yr BP (2 σ : 1617–1788), marking Late Plains Archaic use. Stratum V dates to 1380 cal yr BP (2 σ : 1341–1509). Stratum IV dates to 1128 cal yr BP (2 σ : 1063–1233), representing the final phase of intensive use. These dates span ~700 years (ca. 1800 and 1100 cal yr BP), consistent with point typology and stratigraphic

Bergstrom Site
24JT0893
Area A Unit 3
East Profile

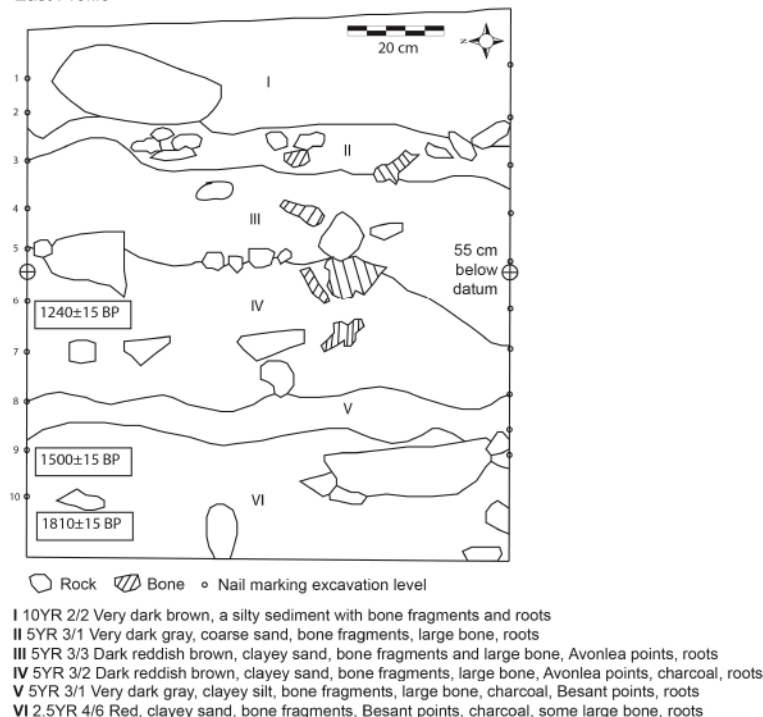


FIGURE 2

Stratigraphic profile and cultural chronology of Unit 3 at the Bergstrom site. See supplement for photograph of pit wall (Supplementary Figure S1).

TABLE 1 AMS radiocarbon dates and calibrated calendar ages from Unit 3 excavation profile at the Bergstrom site, Montana, USA.

Lab no.	Unit	Depth (cm)	^{14}C age $\pm 2\sigma$ error	Cal yr BP (2 σ range)	Material dated
161657	Unit 3, stratum IV	60	1240 $\pm$ 15 BP	1128 (1063, 1233)	Charcoal
161658	Unit 3, stratum V	90	1500 $\pm$ 15 BP	1380 (1341, 1509)	Charcoal
161659	Unit 3, stratum VI	105	1810 $\pm$ 15 BP	1707 (1617, 1788)	Charcoal

All samples measured at NOSAMS Laboratory, Woods Hole Oceanographic Institution.

order. No radiocarbon dates or diagnostics postdate ca. 1100 cal yr BP, indicating cessation of detectable use at this locality.

Paleoecological chronology and environmental context

Sediment core chronology

An age-depth model for cores RBC19 and RBC20 (11 AMS dates) shows variable sedimentation through the Holocene (Table 2, Figure 3). The composite record spans more than 12 ka BP and includes both gradual accumulation and multi-century intervals of reduced deposition. Sedimentation during the mid-Holocene (< 0.01 cm yr⁻¹ between 10.5–2 ka BP) was markedly slower than during earlier and later intervals, consistent with widespread regional aridity and reduced moisture across the Northern Great Plains (Grimm et al., 2011; Shuman and Marsicek, 2016) (Supplementary Table S1).

Deposition resumed at higher rates during the late Holocene, averaging ~0.02 cm yr⁻¹ from 2000–1000 cal yr BP and increasing to ~0.15 cm yr⁻¹ near 900–800 cal yr BP. This late Holocene increase suggests renewed sediment supply or more frequent high-flow

events under wetter conditions. Rates returned to background levels thereafter, with localized spikes around 400 cal yr BP (~0.35 cm yr⁻¹) and ~0.08 cm yr⁻¹ in the most recent two centuries, possibly reflecting cooler and wetter conditions during the Little Ice Age followed by Euro-American land disturbance. The riparian record spans the period of archaeological use and extends well beyond abandonment, providing environmental context before, during, and after human activity.

Vegetation dynamics through time

Pollen from Red Bluff Creek core indicates relatively stable upland and riparian communities during site use and after abandonment (Figure 4; Supplementary Table S2). Throughout 1800–1100 cal yr BP, Poaceae (10–30%) and Cyperaceae (15–30%) remain steady, and *Populus* persists at 2–6%, consistent with stable riparian woody cover and groundwater. *Populus* peaks (~8–10%) at ~400–200 cal yr BP, then declines during the Euro-American period, likely reflecting historic clearing. Rosaceae expands in recent centuries, likely establishing after the loss of larger riparian trees/shrubs. Graminoids (Poaceae, Cyperaceae) remain substantial throughout, indicating sustained habitat suitability for large herbivores before and after hunting ceased.

TABLE 2 AMS radiocarbon dates and calibrated calendar ages from sediment cores RBC19 and RBC20 collected along the riparian margin of Red Bluff Creek, adjacent to the Bergstrom site, Montana, USA.

Lab no.	Core	Depth (cm)	^{14}C age $\pm 2\sigma$ error	Cal yr BP (2 σ range)	Material dated
Surface	RBC19	0	-69	-68	–
161662	RBC19	13	0 $\pm$ 30	124 (42, 199)	Bulk sediment
161663	RBC19	19	50 $\pm$ 30	238 (188, 270)	Bulk sediment
161664	RBC19	25	350 $\pm$ 15	332 (311, 365)	Bulk sediment
161665	RBC19	43	290 $\pm$ 15	404 (373, 429)	Bulk sediment
161666	RBC19	49	230 $\pm$ 15	423 (400, 467)	Bulk sediment
161667	RBC19	60	470 $\pm$ 15	513 (492, 535)	Bulk sediment
161668	RBC19	70	915 $\pm$ 15	761 (699, 826)	Bulk sediment
161669	RBC19	90	860 $\pm$ 15	889 (844, 1112)	Bulk sediment
161671	RBC19	119	2170 $\pm$ 15	2240 (2055, 2295)	Plant material
167330	RBC20	193	9910 $\pm$ 40	11279 (10814, 11459)	Bulk sediment
167333	RBC20	234	10500 $\pm$ 45	12558 (12255, 12674)	Bulk sediment
161670 ^a	RBC19	111	3870 $\pm$ 20	NA	Plant material

All samples measured at NOSAMS Laboratory at Woods Hole Oceanographic Institution.

^aSample rejected.

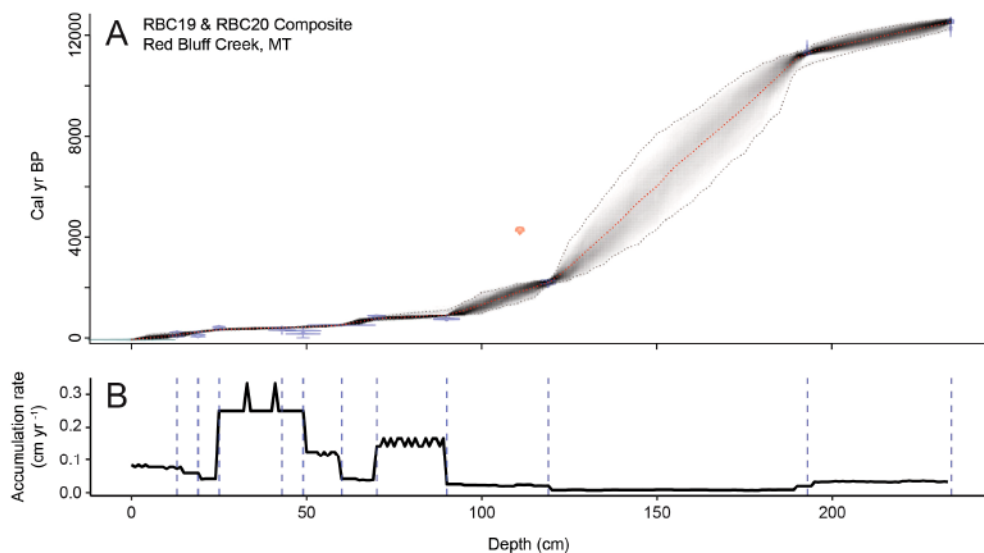


FIGURE 3

Composite age-depth model and sediment accumulation rate for RBC19 & RBC20 from Red Bluff Creek, Montana. (A) Composite age-depth model for Red Bluff Creek based on 11 AMS radiocarbon dates (blue density curves) from riparian sediments collected adjacent to the Bergstrom archaeological site. One radiocarbon date was rejected from the model (red density curve). The dotted red line represents the weighted mean age at a given depth, gray shading and dotted gray lines represent the distribution of the most likely age-depth model and 95% posterior density intervals. (B) Sediment accumulation rate over core depth. The dotted lines indicate depths of radiocarbon samples.

Fire history

Charcoal accumulation (CHAR) and background charcoal (BCHAR) are low through most of the late Holocene, with more fire in recent centuries (Figure 5; Supplementary Table S3). Low CHAR during intervals of severe drought suggests limited fuel and/or predominately low-severity herbaceous fires that are under-represented in macroscopic charcoal influx. During archaeological use (1800–1100 cal yr BP), CHAR and BCHAR remain low. Around abandonment (ca. 1100 cal yr BP) there is no charcoal increase. Peaks in the last few centuries, including a 20th-century maximum and a cluster ca. 200 cal yr BP, may reflect fuel buildup on adjacent slopes under cooler, wetter Little Ice Age conditions (Cook et al., 2007; Marlon et al., 2012; Iglesias et al., 2018). Overall, burning does not appear to have constrained site use or triggered abandonment.

Large herbivore presence

Dung-fungal spores and botanical indicators record large-herbivore activity through the last millennium, with higher values after abandonment (Figure 5). *Sporormiella*-type spores are rare until ca. 500 cal yr BP and persist into recent samples. *Selaginella densa*-type spores vary (0–6%) and gradually increase between 1500–400 cal yr BP; this lycophyte is characteristic of early-successional/disturbed grasslands and sensitive to burning (Hubbard, 1951; Shay et al., 2001; Grimm et al., 2011).

Regional paleoclimate

Tree-ring PDSI reconstructions identify clustered severe droughts between ca. 1700 and 700 cal yr BP that overlap both the use and

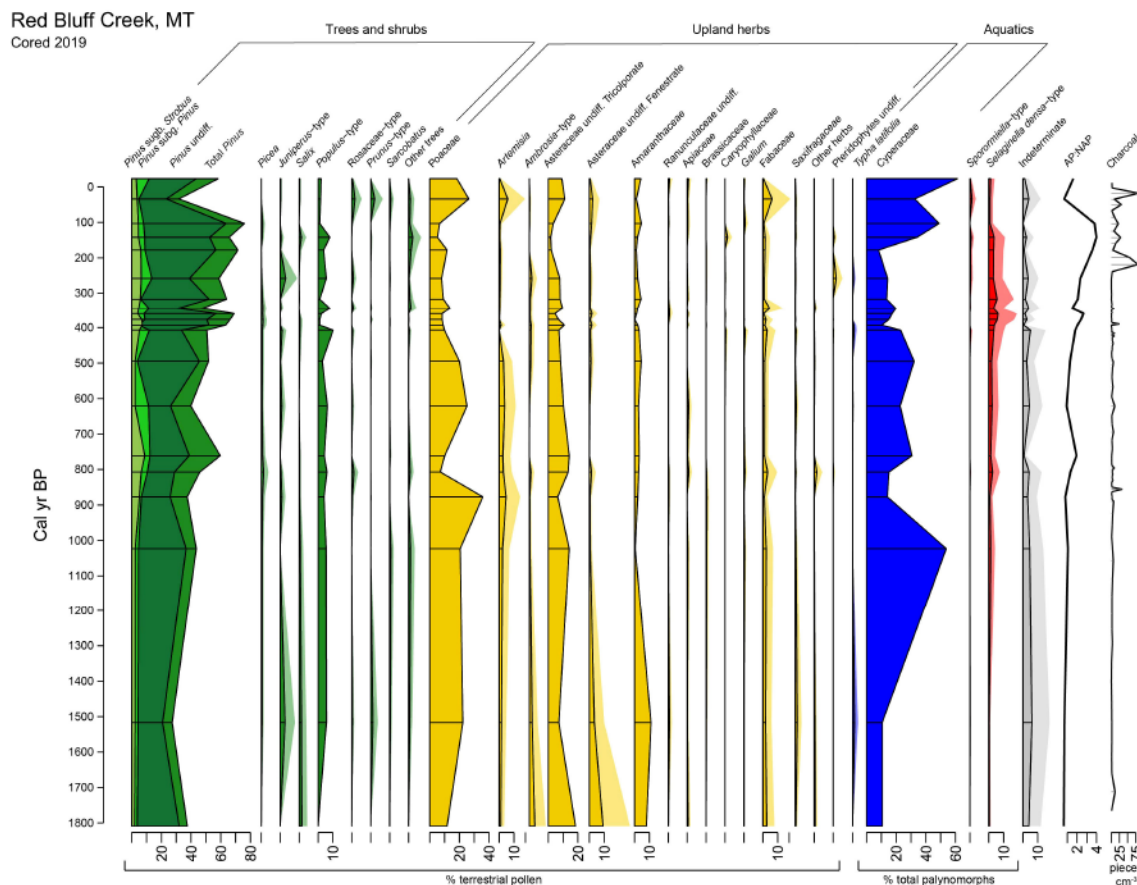
abandonment at Bergstrom (Figure 5). The highest-magnitude drought event (1342–1323 cal yr BP; mean summer PDSI -2.65) coincides with the Besant–Avonlea transition. The period of abandonment includes the second (1008–991 cal yr BP) and third (924–910 cal yr BP) highest-magnitude droughts. Spring-fed flow at Red Bluff Creek may have buffered moderate droughts, but the most severe episodes likely reduced forage and processing water and affected herd distributions. The riparian system appears stable: sedimentation, *Populus* pollen, and herbivore-indicator spores indicate ecological continuity and large herbivore presence after abandonment.

Regional bison occurrence patterns

Archaeological and paleontological bison occurrences within 600 km of Bergstrom were analyzed to test the population tracking hypothesis (H0), which predicts archaeological and paleontological frequencies should covary proportionally through time.

The A:P ratio varied significantly across major time periods ($\chi^2 = 28.92$, $df = 3$, $p < 0.001$; Supplementary Figure S2), increasing 5.5-fold from 2.12:1 in the Pleistocene to 11.6:1 in the late Holocene. Intermediate values of 3.17:1 (early Holocene) and 4.24:1 (mid-Holocene) document progressive divergence between archaeological and paleontological frequencies through the Holocene. This pattern demonstrates that archaeological hunting intensity varied far more than paleontological bison presence.

Time-series analysis using 100-year bins revealed a significant negative correlation between archaeological and paleontological frequencies ($r_s = -0.32$, $p < 0.001$; Supplementary Figure S2). Counter to the prediction of proportional covariation, archaeological



Archaeological and paleontological frequencies exhibit a significant negative correlation, documenting progressive hunting intensification through time (Supplementary Figure S2). This pattern is incompatible with population tracking, which predicts positive correlation between the two records. A 5.5-fold increase far exceeds plausible variation in bison population densities and instead reflects the progressive “crowding out” of paleontological assemblages as human environmental footprints expanded. Since the early Holocene, archaeological frequencies remain consistently above paleontological frequencies throughout the record, indicating continuous regional hunting that varied in intensity but never ceased.

This trend was likely driven by multiple processes. As human populations grew (Kelly et al. 2025, PNAS), increased hunting, scavenging and processing converted natural mortality into archaeological contexts. Expanded landscape use increased spatial overlap between human activities and bison populations, bringing human presence into closer association with bison death events. More intensive use of bison products incorporated more anatomy into material culture. Consequently, archaeological contexts increasingly dominate the regional death record, not only because humans killed more bison, but also because human activity progressively intersected with more bison mortality events.

The intensification peak during a period of recurring severe drought (1700–700 cal yr BP) contradicts predictions that environmental stress should reduce hunting activity. Rather than declining, A:P ratios reached their highest values during this arid interval, suggesting that droughts restructured hunting organization rather than suppressing regional exploitation. Under water-limited conditions, sites with reliable water sources capable of supporting intensive processing operations likely became focal points, while hydrologically marginal localities like Bergstrom became impractical for both bison and hunters.

Site-specific environmental evidence

The Bergstrom sequence records approximately 700 years of intermittent bison kills ending near 1100 cal yr BP. Riparian proxies indicate local habitat conditions likely remained suitable for bison after hunting ceased. Pollen of graminoids, sagebrush, and *Populus* remain stable; charcoal influx stays low; and herbivore-indicator spores persist after the final cultural layer (Figure 5D), demonstrating that the site retained ecological suitability for bison.

Sediment accumulation rates in Red Bluff Creek cores indicate the site's drought sensitivity. Accumulation rates remained below 0.01 cm yr⁻¹ during most of the Holocene, consistent with region-wide aridity (Grimm et al., 2011; Shuman and Marsicek, 2016; Figure 5D). Low accumulation rates imply reduced water availability in the creek system. Earlier droughts overlap with gaps between dated occupations (ca. 1710, 1380, 1130 cal yr BP), establishing correspondence between regional aridity and reduced site use (Figures 5B, C). This sensitivity likely made Bergstrom less viable during droughts, when limited water would have constrained both bison congregation and intensive processing operations.

The most severe drought (1342–1323 cal yr BP) overlaps with the stratigraphic transition from Besant to Avonlea projectile points at Bergstrom and regionally (Peck, 2011), raising the possibility that hydrological stress influenced technological or organizational change during this pivotal transition.

Archaeological context and assemblage characteristics

The Bergstrom artifact assemblage provides evidence of site function and intensity. Low lithic density, absence of drive features, and limited processing debris are consistent with opportunistic use by small, mobile groups. In contrast, after ca. 2000 cal yr BP, bison hunting underwent economic and organizational intensification across the Northern Great Plains, reflected in expansion of large, spatially concentrated communal hunting complexes employing drive lines, corrals, and jump features to harvest large numbers of animals (Brink, 2008; Bamforth, 2011; Zedeño et al., 2014; Bethke et al., 2018; Lee et al., 2019). These operations required dependable water, substantial processing space, coordinated labor, and often multi-day or multi-week occupation. The final dated occupation at Bergstrom (1130 cal yr BP) coincides with regional proliferation of infrastructure-intensive sites.

Hypothesis evaluation

H0. population tracking

The population tracking hypothesis predicts hunting should resume when droughts end and bison populations recover. This prediction is not supported. Paleontological and archaeological evidence demonstrates that bison persisted regionally after 1100 cal yr BP (Figure 5A), and droughts eventually ameliorated, yet Bergstrom was not reoccupied. Regional A:P ratios remained elevated, confirming sustained hunting intensity despite Bergstrom's exclusion. Early occupation gaps align with drought intervals (Figures 5B, C), suggesting initial sensitivity to climate-driven fluctuations, but permanent abandonment during peak regional hunting activity indicates that factors beyond prey abundance determined site viability.

H1. ecological transformation

The ecological transformation hypothesis (H1) is not supported by paleoecological evidence. Pollen records indicate persistent open grassland with stable graminoid (Poaceae, Cyperaceae) and riparian woody vegetation (*Populus*) before, during, and after the final occupation (Figures 4, 5D). Charcoal influx remained consistently low throughout the sequence, showing no directional change in fire activity. Herbivore indicators point to continued large-herbivore presence after hunting ceased, demonstrating that the site remained ecologically suitable for bison. In contrast to findings from Two Medicine Valley, where Roos et al. (2018) documented that intentional burning coincided with communal bison hunts, the Bergstrom record shows no comparable relationship between fire activity and hunting episodes. The absence of persistent

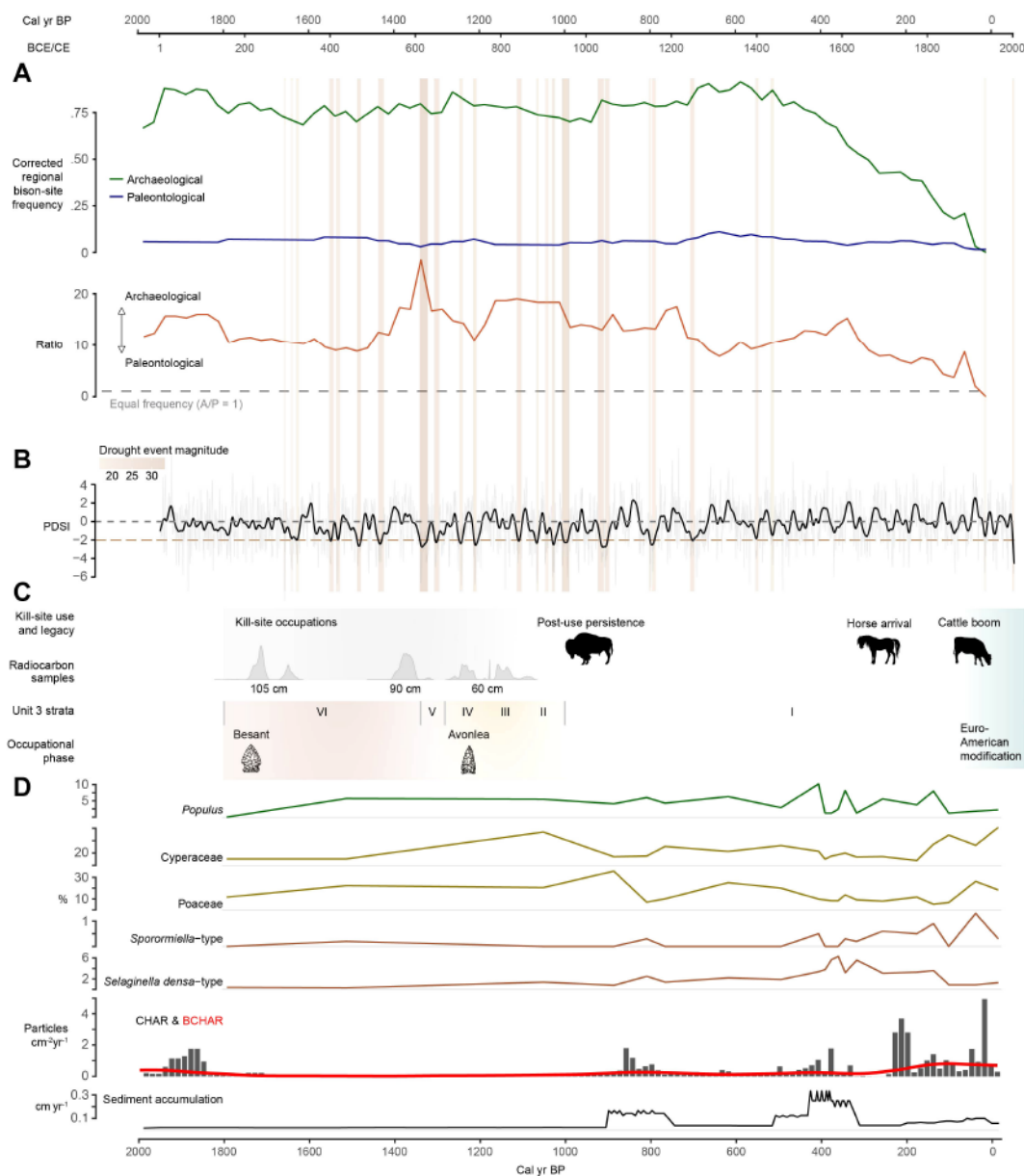


FIGURE 5

Multiproxy evidence for episodic use and long-term abandonment of the Bergstrom site, Montana. (A) Regional frequencies of archaeological (green) and paleontological (blue) bison sites within 600 km of Bergstrom, corrected for taphonomic bias (Surovell et al., 2009) and binned at 25-year intervals. The archaeological and paleontological ratio (A:P, orange line, bottom panel). Dashed line at A:P = 1 indicates equal frequencies (B) Summer Palmer Drought Severity Index (PDSI) reconstruction at 110°W, 45°N (Cook et al., 2007, 2010) documents repeated high-magnitude (duration × severity > 15) droughts (brown vertical bars), annual variability (gray line) and [10-yr? spline – used standard for the dataset]. Dashed lines mark PDSI values of 0 (dark gray) and -4 (orange, extreme drought threshold). (C) Stratigraphic profile and cultural chronology of Unit 3 showing six depositional layers (Strata I–VI), with cultural material (bone, charcoal, projectile points) concentrated in Strata III–VI. Three radiocarbon dates (105 cm, 90 cm, 60 cm) bracket ca. 700 years of intermittent bison hunting between ca. 1800 and 1100 cal yr BP, spanning Besant and Avonlea occupational phases. Sterile Stratum I marks post-abandonment sedimentation. (D) Paleoecological records from Red Bluff Creek sediment core RBC19 showing continuity in riparian woody vegetation (*Populus*, green), wetland and upland graminoids (*Cyperaceae* and *Poaceae*, yellow/brown), herbivore presence indicators (*Sporormiella*-type and *Selaginella densa*-type spores, orange/brown), charcoal accumulation rate (cm yr^{-1} , black line, bottom panel) spanning the period of site use and extending beyond abandonment.

environmental shifts indicates that local habitat changes did not drive abandonment.

H2. procurement reconfiguration

Regional shifts toward communal hunting operations provide a plausible mechanism for Bergstrom's declining utility. In this

changing regional context, small intercept sites likely yielded diminishing relative returns as group sizes increased and processing demands intensified. The Bergstrom assemblage characteristics support this interpretation: the site's opportunistic, small-group signature contrasts with contemporaneous infrastructure-intensive communal operations.

However, H2 alone does not fully explain the timing and permanence of abandonment. Regional reorganization toward communal hunting was a multi-century process beginning well before 1100 cal yr BP, yet Bergstrom continued to be used episodically. Why was this particular interval the final one? And why was the site never reoccupied in subsequent centuries when bison remained regionally abundant? These questions require consideration of additional factors.

H3. converging constraints

The constraint convergence hypothesis (H3) provides the most complete explanation by integrating logistical reorganization (H2) with hydrological and competitive pressures that converged during a critical window. The final occupation (ca. 1130 cal yr BP) immediately preceded a sequence of severe multi-decadal droughts, including the second and third most extreme events of the last two millennia (1008–991 and 924–910 cal yr BP; [Figures 5B, C](#)).

The cluster of extreme droughts after 1100 cal yr BP would have imposed multiple constraints. First, limited water availability at the hydrologically sensitive Red Bluff Creek site would have constrained both bison congregation and the processing operations that characterize kill sites. Second, during water-limited conditions, hunters would have increasingly concentrated effort at sites with more dependable water sources. Third, as communal hunting intensified regionally, competition for prime hunting localities increased, making marginal sites like Bergstrom less attractive to locations with superior hydrology and infrastructure potential. Finally, multi-decadal drought persistence would have created sustained disadvantages, inhibiting opportunistic reoccupation during brief favorable intervals. [Table 3](#) compares hunting system attributes across time periods, illustrating how Bergstrom's characteristics increasingly diverged from Late Prehistoric norms.

We interpret this pattern as evidence for adaptive reorganization of late Holocene hunting systems. Repeated droughts and rising organizational demands progressively favored sites with advantageous topography, hydrology, and infrastructure. Marginal sites were abandoned while the best localities became loci of increasingly intensive communal hunting. This filtering process would have concentrated effort at a smaller number of high-capacity sites, fundamentally reshaping the spatial and organizational structure of bison procurement across the Northern Great Plains. This form of localized abandonment amid regional continuity parallels mid-Holocene subsistence mosaics described by [Breslawski \(2023\)](#), where

adaptive restructuring produced discontinuous occupation across landscapes.

This interpretation generates testable predictions for future research: (1) sites with perennial water sources should exhibit more continuous use across drought intervals than hydrologically marginal locations; (2) sites with substantial infrastructure investment should show longer use histories and greater material accumulations; (3) small sites lacking infrastructure should be disproportionately abandoned during periods of severe or sustained drought. Testing these predictions will require systematic comparison of kill-site chronologies and environmental settings, including dated stratigraphic sequences, isotopic indicators of water stress (e.g., $\delta^{18}\text{O}$ in bison enamel), and spatiotemporal analyses of site use within regional hunting networks.

Interpretive limits

Three stratigraphically coherent radiocarbon ages bracket about 700 years of use and identify at least three kill episodes but cannot resolve the frequency or duration of individual occupations. The absence of material after 1100 cal yr BP could represent true abandonment or low-impact use below detection thresholds. Higher-resolution dating could refine our understanding of site use episodicity.

Herbivore-indicator spores record large herbivore presence but are not taxon-specific. Pollen and charcoal reflect conditions near the coring site but may miss short-term or patch-scale variability. Agricultural modification likely reduced the visibility of small cairns or drive lines, though the excavation units appear unaffected by early 20th-century bone collecting ([Davis, 1978](#)).

While the absence of infrastructure does not conclusively demonstrate opportunistic hunting, the intermittent use intervals and low artifact density are consistent with small-group intercept activity. Social processes such as territorial reorganization, ceremonial avoidance, shifts in social institutions, or changing group composition may also have influenced which sites were used or avoided ([Zedeño et al., 2014](#); [Zedeño, 2017](#)), though such factors cannot be evaluated with our datasets.

Integration of past dynamics with contemporary management

The Bergstrom record illustrates how bison hunting systems persisted through environmental variability. These systems

TABLE 3 Comparison of hunting system attributes across the Late Archaic/Early Late Prehistoric, Late Prehistoric, and Bergstrom site use.

Attribute	Late Archaic/Early Late Prehistoric	Late Prehistoric	Bergstrom site
Time period	ca. 3000–1000 cal yr BP	ca. 1350–250 cal yr BP	ca. 1800–1100 cal yr BP
Reuse pattern	Episodic, dispersed	Frequent reuse of fixed sites	Episodic use over ~700 years
Infrastructure	Minimal or ephemeral	Extensive (drive lines, jumps)	None preserved (likely minimal)
Group organization	Small-group, opportunistic	Large coordinated communal hunts	Small-group, opportunistic
Kill scale	Variable, often moderate	Large-scale	Moderate

Patterns of reuse, infrastructure, group organization, and kill scale draw on regional syntheses and case studies of bison hunting in the Northern Great Plains ([Reeves, 1990](#); [Frison et al., 1991](#); [Brink, 2008](#); [Cooper, 2008](#); [Bamforth, 2011](#); [Peck, 2011](#); [Zedeño et al., 2014](#); [Kornfeld et al., 2016](#); [Bethke et al., 2018](#)).

exhibited spatial flexibility and adaptive disengagement. This millennial-scale perspective offers actionable principles for contemporary bison management across the North American Bison Management System (Martin et al., 2021).

Principle 1: heterogeneity as adaptive capacity

Late Holocene hunting relied on a mosaic of sites with varying use intensities. Many sites were used episodically and eventually abandoned while regional systems persisted (Reeves, 1990; Peck, 2011), preventing localized depletion and allowing recovery between hunts. Modern operations typically emphasize predictability and uniform resource use within fixed boundaries (Freese et al., 2007; Gates et al., 2010), creating vulnerability when conditions shift. Strategies to restore adaptive capacity include patch-burn grazing that creates shifting mosaics of disturbance (Fuhlendorf and Engle, 2001; Fuhlendorf et al., 2009), stocking rates below carrying capacity to preserve drought-response flexibility, cross-boundary agreements enabling temporary redistribution during stress, and increasing tolerance of greater variability in herd size and distribution rather than static population goals.

Principle 2: avoiding constraint convergence

At Bergstrom, limited processing water converged with rising organizational demands for larger operations, rendering the site impractical. Modern bison operations face analogous convergent pressures including regulatory requirements, infrastructure limitations, market expectations, disease, and climate variability that can simultaneously constrain adaptive options (Martin et al., 2021; Shamon et al., 2022). Optimizing for single objectives (e.g., maximum sustained yield, predictable harvest timing) reduces buffers against perturbation, mirroring the “pathology of natural resource management” where control reduces system resilience (Holling and Meffe, 1996). Practical strategies include maintaining flexibility in processing time and location, building financial reserves to absorb variable production, developing diverse marketing channels, and retaining access to alternative grazing areas during extreme weather.

Principle 3: leveraging bison’s inherent climate resilience

Bison populations persisted through severe droughts while human use patterns shifted. Contemporary management can harness this adaptive potential by reducing artificial constraints by maintaining habitat connectivity between seasonal ranges, preserving access to diverse forage types across environmental gradients, allowing seasonal and interannual movement rather than year-round occupancy of fixed areas, and low to moderate stocking rates that allow animals to track resource variability. Management systems that restrict movement or consistently operate at carrying capacity may inadvertently constrain the adaptive flexibility observed in long-persistent systems of the past.

The Bergstrom case demonstrates that intermittent use of individual sites was a common occurrence in bison hunting systems. This pattern was likely a result of multiple factors (e.g., intentional cultural hunting strategy, change in environmental/forage conditions, shifting organizational structure of hunting)

and may be critical for persistence of large prey species at larger geographic scales (Holling and Meffe, 1996; Sanderson et al., 2008). The archaeological record supports shifting from optimizing for predictability toward protecting adaptive capacity, not necessarily abandoning productivity goals or modern infrastructure, but recognizing that heterogeneity, redundancy, and flexibility are fundamental to long-term resilience under climate uncertainty.

Conclusion

The Bergstrom site documents approximately 700 years of episodic bison hunting in central Montana ending near 1100 cal yr BP without evidence of local ecological degradation. Vegetation remained stable, fire activity stayed low, and herbivore indicators suggest continued large herbivore use after hunting ceased. The abandonment coincided with severe multi-decadal droughts and regional expansion of infrastructure-intensive communal hunting, indicating that hydrological constraints converged with shifting procurement logistics to render this small, water-limited site impractical to hunters.

Regional patterns of archaeological and paleontological bison occurrences reveal contrasting responses to climate variability. Archaeological frequencies declined during clustered droughts while paleontological occurrences remained stable, demonstrating that bison populations persisted as patterns of human use shifted. This divergence, with peak hunting intensity coinciding with severe drought, indicates that droughts restructured hunting organization rather than reducing regional bison availability. The capacity to disengage from marginal sites appears to have been a structural feature of late Holocene hunting systems that exhibited both reduced localized pressure and regional persistence.

Contemporary bison management operates under fixed boundaries and intensive regulation that may constrain the spatial flexibility and adaptive disengagement observed in archaeological systems. Strategies preserving heterogeneity in site use, maintaining habitat connectivity, and managing below carrying capacity can sustain bison populations through climate uncertainty by retaining adaptive mechanisms that characterize long-persistent systems.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

JW: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. MN: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. MA: Data curation, Formal Analysis, Investigation, Methodology,

Writing – review & editing. SE: Investigation, Methodology, Supervision, Writing – review & editing. GF: Data curation, Investigation, Writing – review & editing. DM: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. Generative AI (Claude 3.5 Sonnet,

Anthropic) was used solely for language editing; all scientific interpretations and conclusions were produced by the authors.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fcsc.2025.1688950/full#supplementary-material>

SUPPLEMENTARY FIGURE 1

Photograph of excavation pit profile of Unit 3, Bergstrom site.

SUPPLEMENTARY FIGURE 2

Regional analysis of archaeological vs. paleontological bison occurrences within 600 km of Bergstrom, Montana. (A) Temporal trends in archaeological (green) and paleontological (blue) bison site frequencies, corrected for taphonomic bias (Surovell et al., 2009) and binned at 100-year intervals. (B) Archaeological to paleontological ratio (A:P) through time. The dashed horizontal line at A:P=1 represents equal archaeological and paleontological frequencies. (C) Mean A:P ratios by major time periods (Pleistocene, early Holocene, mid-Holocene, and late Holocene), demonstrating statistically significant variation across periods ($\chi^2 = 28.92$, $df = 3$, $p < 0.001$). Sample size (n_A = archaeological occurrences, n_P = paleontological occurrences) are shown for each period.

SUPPLEMENTARY TABLE 1

Age-depth model results for Red Bluff Creek sediment cores RBC19 and RBC20. Depth (cm), calibrated age ranges (95% confidence intervals), median and mean ages (cal yr BP), and sediment accumulation rates (cm yr^{-1}) derived from Bayesian age-depth modeling using 11 AMS radiocarbon dates.

SUPPLEMENTARY TABLE 2

Pollen percentage data from Red Bluff Creek sediment cores RBC19 & RBC20 (depth units in cm).

SUPPLEMENTARY TABLE 3

Macroscopic charcoal counts from Red Bluff Creek sediment core RBC19, Montana. Data include sample depth (cm), sediment volume (cm^3), charcoal counts (particles > 125 μm) used to calculate charcoal accumulation rates (CHAR) and background charcoal (BCHAR).

SUPPLEMENTARY TABLE 4

Radiocarbon-dated bison occurrences within 600 km of the Bergstrom site classified as archaeological ($n = 579$) or paleontological ($n = 76$) contexts. Data includes site name, classification code (A = Archaeological, P = Paleontological), data source (CARD or Neotoma databases), calibrated age ranges (IntCal20), stratigraphic context, coordinates, primary citations, and distance from Bergstrom. Dataset adapted from Wendt et al. (2022).

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