INL/JOU-16-38997
Accepted Manuscript

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June 2016

Prepared for the U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Journal of Anthropological Archaeology xxx (2016) xxx-xxx

Contents lists available at ScienceDirect

Journal of Anthropological Archaeology

journal homepage: www.elsevier.com

Holocene cold storage practices on the eastern Snake River Plain: A risk-mitigation strategy for lean times

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ARTICLE INFO

Article history:
Received 28 February 2016
Received in revised form 23 May 2016
Available online xxx

Keywords:
Snake River Plain
Cold storage caves
Bison
Risk
Z-score model

ABSTRACT

Previous archaeological research in southern Idaho has suggested that climate change over the past 8000 years was not dramatic enough to alter long-term subsistence practices in the region. However, recent isotopic analyses of bison remains from cold storage caves on the Snake River Plain contest this hypothesis. These results, when examined against an archaeoclimate model, suggest that cold storage episodes coincided with drier, warmer phases that likely reduced forage and water, and thus limited the availability of bison on the open steppe. Within this context we build a risk model to illustrate how environment might have motivated cold storage behaviors. Caching bison in cold lava tubes would have mitigated both intra-annual and inter-annual food shortages under these conditions. Our analysis also suggests that skeletal fat, more than meat, may have influenced the selection, transport and storage of bison carcass parts. Deciphering when and how cold storage caves were utilized can ultimately provide a more comprehensive understanding of foraging behaviors in a broad range of hunting-gathering economies.

1. Introduction

Previous investigations of prehistoric land use patterns on the eastern Snake River Plain (SRP) suggest that shifts in Holocene climate had little impact on long-term subsistence and settlement patterns in the region (see Henrikson, 2002 and discussion therein). This view derives from a series of large-scale, regional studies that show similarities between the seasonal round employed by foragers over thousands of years and 19th Century ethnographic accounts of the Shoshone, Bannock, and Paiute. Moreover, the Holocene archaeological record of southeast Idaho contains numerous sites documenting millennia of occupation, reflecting a level of continuity that belies the possibility of significant climate-induced adjustments in resource use.

We, however, suspect that this picture of long-term, adaptive stasis reflects more a deficiency in data, rather than a complete and accurate picture of the relationship between SRP environment and human adaptation. Lacking within this context have been any rigorous attempts to tie environmental trends with patterns observed in the SRP archaeological record. Over the past several years, efforts to expand our knowledge of Holocene climate have been initiated through analyses of the relationships between bison remains recovered from cold lava tubes on the eastern SRP and several paleoenvironmental indicators. In fact, recently acquired radiocarbon dates from these bison storage facilities suggest that the relationships between human behavior and the SRP environmental record are both more complicated and variable than previously thought.

Between 1987 and 2004, seven ice caves on the eastern SRP were discovered to contain sagebrush features designed to keep bison products insulated and frozen (Henrikson, 1996, 2003, 2004; Henrikson et al., 2006). These caves are scatted across the sagebrush steppe in Pleistocene-aged lava flows buried by a relatively thin layer of aeolian sediments (Fig. 1). Test excavations in five of these caves indicate that bison were the prey of choice for cold storage. These cold, lava tubes on the mid-latitude SRP provided a way to freeze bison remains throughout the year, despite significantly warmer temperatures during the summer months. Both recent observation and archaeological data suggest that these cold caves likely never became dysfunctional at any time and they maintain temperatures below freezing today (Henrikson, 2002, 2003; Henrikson and Guenther, 2012). Yet, despite the long-term dependability of these facilities, radiocarbon dates suggest that cold storage of bison occurred episodically during the Holocene (Table 1, Fig. 2).

Storage represents one solution to the problems posed by risk, the probability that a forager will experience a resource shortfall (Winterhalder et al., 1999, see also Morgan, 2012 for an exhaustive overview of hunter-gatherers and storage). Non-human foragers store food in times of unreliable, unpredictable and/or low environmental productivity (Brodin and Clark, 2007; Smith and Reichman, 1984; Vander Wall, 1990). Among human foragers, archaeologists often view storage as a mechanism related to settlement systems, social complexity and, much like non-human foragers, as a means for coping with environmental variability (Morgan, 2012: 717). In this study, we focus on the latter.

Viewed within an environmental context, storage provides a solution to two important subsistence problems (Morgan, 2012: 717).

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http://dx.doi.org/10.1016/j.jaa.2016.05.005

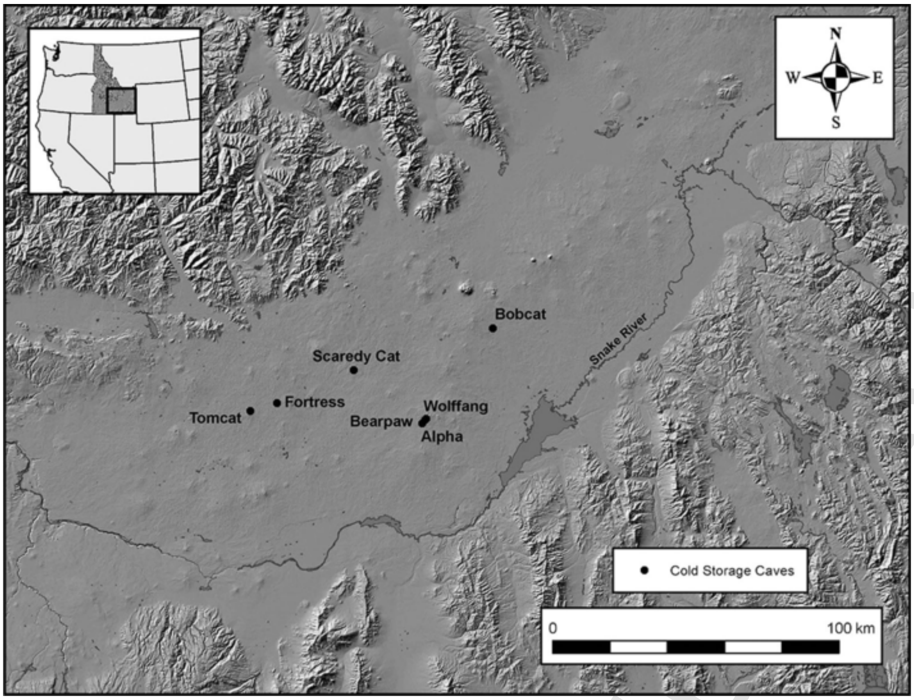

Fig. 1. Map of the Snake River Plain showing the locations of cold-storage caves discussed in this paper. Alpha and Black Widow (not identified) Caves share a location. Bearpaw and Wolffang cave collections have yet to be analyzed and are not included in this study.

First, storage allows foragers to average subsistence returns across periods of seasonally variable environmental productivity (Goland, 1991). Consequently, storage can serve as an important adaptation for foragers living in mid/high-latitude environments characterized by spatially disparate and seasonally scheduled resources. In such seasonal environments, storage often takes the form of an over-wintering strategy (Binford, 1980, 1990, 2001; Rowley-Conwy and Zvelebil, 1989). Second, storage can serve as an insurance mechanism used to cope with the risks of relying on natural resources in circumstances characterized by variation in multi-year environmental productivity. In the latter case, storage does not mitigate expected seasonal shortfalls, but instead, provides a strategy for reducing variability around some expected long-term outcome. In either case, the ultimate goal is one of ensuring that minimum subsistence/survival thresholds are met. On the SRP, bison likely represented an important resource characterized by both long-term and seasonal variability in availability.

Long-term fluctuations in the SRP climate regime provide one possible prime-mover behind variability in bison encounter rates. Faunal studies often address variability in the hunter-gatherer subsistence record and these often focus on the relationship between subsistence decisions and environmentally driven trends in prey availability. Moreover, such studies often speak to diet breadth and have recently done so for the SRP and nearby northern Great Basin (e.g. Byers and Broughton, 2004; Henrikson, 2004). However, encounter rates and return rates in such contexts are viewed as averages, while in the real world, these rates can vary around a mean value, and at times do so considerably. Moreover, such models do not always account for some behaviors seen in the archaeological record. The delayed return nature of bison storage on the SRP represents one case in point.

In this paper, we take a long-term, trans-Holocene look at storage as a risk-related adaptation. In the analyses that follow, we use the SRP example to unpack one set of motivations behind the evolution of hunter-gatherer storage. Within this context, we explore the simple question, should we expect the storage of bison on the SRP and if so, under what circumstances would it make sense? Although the mere existence of cold, lava-tube storage features would suggest that they would always be utilized, we argue instead that this phenomenon represents a risk-mitigation strategy employed in the face of climate-driven fluctuations in the availability and predictability of important food resources.

To pursue this research question, we first build a risk model for the relationship between bison and subsistence on the SRP. We use this model to leverage a series of predictions for the conditions under which storage should be expected, suggesting that bison would have been stored during times of declining environmental productivity, falling bison numbers and, consequently, increasing unpredictability in encounter rates with these animals. To evaluate this hypothesis, we array several archaeological datasets, including zooarchaeological measures of prey abundance, bison skeletal element frequencies from cold storage caves and measures of bison nutritional utility, against paleoenvironmental and region-wide SRP archaeological datasets to evaluate the relationships between storage, environmental conditions and prey abundances.

2. Understanding risk: the Z-score model

Stephens (1981, Stephens and Charnov, 1982) developed the Z-score risk model in response to observations that non-human foragers display food preferences that are sensitive to variability in the probability distribution of subsistence outcomes. In other words, foragers can make subsistence choices within the context of risk management (Bettinger et al., 2015; Stephens, 1990). This approach differs from many of the better-known optimal foraging models that take a deterministic (focused on an expected mean outcome) view of foraging decisions (Winterhalder, 1986).

Table 1
Radiocarbon data for Snake River Plain cold-storage caves.

Site name	Sample description	Radiocarbon	Two sigma range cal. BP	
		Age BP	Minimum	Maximum
Alpha Cave	*B. bison* vertebrae	960 ± 40	786	938
Alpha Cave	*B. bison* radius	980 ± 40	795	958
Alpha Cave	*B. bison* scapula	990 ± 40	890	963
Black Widow Cave	*B. bison* scapula	1000 ± 40	891	975
Alpha Cave	*B. bison* ulna fragment	1050 ± 40	915	1058
Alpha Cave	*B. bison* innominate fragment	1050 ± 40	915	1058
Alpha Cave	*B. bison* ulna fragment	1070 ± 40	927	1059
Tomcat Cave	*Artemisia* sp. stalk	1170 ± 60	962	1188
Tomcat Cave	*Artemisia* sp. stalk	1240 ± 60	1053	1290
Fortress Cave	*C. canadensis* antler tine	1350 ± 40	1228	1334
Scaredy Cat Cave	Basket fragment	1470 ± 40	1259	1415
Alpha Cave	*C. canadensis* antler tine	1690 ± 40	1259	1701
Alpha Cave	*C. canadensis* antler tine	1880 ± 40	1714	1897
Tomcat Cave	*Artemisia* sp. stalk	2120 ± 60	1966	2209
Tomcat Cave	*Artemisia* sp. stalk	2240 ± 60	2114	2354
Tomcat Cave	*Artemisia* sp. stalk	2350 ± 60	2301	2540
Tomcat Cave	*Artemisia* sp. stalk	2400 ± 60	2339	2549
Scaredy Cat Cave	*U. arctos* femur	2600 ± 60	2676	2849
Bobcat Cave	*B. bison*	2780 ± 80	2750	3777
Alpha Cave	*B. bison* femur fragment	3600 ± 40	3826	3993
Scaredy Cat Cave	*Artemisia* sp. stalk	3810 ± 70	4068	4415
Scaredy Cat Cave	*Artemisia* sp. stalk	3840 ± 70	4078	4425
Scaredy Cat Cave	*Artemisia* sp. stalk	3900 ± 70	4146	4453
Bobcat Cave	*Artemisia* sp. stalk	4110 ± 70	4506	4829
Scaredy Cat Cave	*Artemisia* sp. stalk	4210 ± 60	4569	4865
Bobcat Cave	*Artemisia* sp. stalk	4360 ± 70	4828	5077
Alpha Cave	*C. canadensis* antler tine	4370 ± 50	4839	5056
Scaredy Cat Cave	*B. bison* humerus	4450 ± 40	4957	5093
Scaredy Cat Cave	*Artemisia* sp. stalk	5740 ± 80	6394	6731
Scaredy Cat Cave	*Artemisia* sp. stalk	6370 ± 90	7155	7444
Scaredy Cat Cave	*Artemisia* sp. stalk	6680 ± 80	7434	7665
Scaredy Cat Cave	*Artemisia* sp. stalk	6850 ± 70	7579	7833
Scaredy Cat Cave	*Artemisia* sp. stalk	6930 ± 60	7661	7873
Scaredy Cat Cave	*Artemisia* sp. stalk	8190 ± 100	8972	9460

A Z-score measures how many standard deviations (s) an observation (n) sits above or below the mean (u) of a population of interest. The equation $Z = (n - u)/s$ expresses this relationship. Archaeologists can operationalize the Z-score model by setting u and s to the mean and standard deviation for the outcome for a given behavior, with n representing the caloric return-rate threshold necessary for survival (Bettinger et al., 2015; Winterhalder et al., 1999). In many studies, archaeologists measure such outcomes as a return rate, and since we focus on subsistence behaviors, we use calories/hour as the relevant measure. As a result, Z-scores identify the probability that a given subsistence choice will provide a return rate above the survival threshold (Fig. 3a).

It is important to understand the role of variability (s) within this model (Bettinger et al., 2015; Winterhalder et al., 1999). If the mean outcome for a subsistence behavior is greater than the survival threshold, $u > n$, then Z will be negative (Fig. 3b). Increasing variability (s) has the effect of making Z less negative and, consequently, representative of a lower probability of meeting the subsistence threshold. If the mean outcome for a subsistence behavior is less than the survival threshold, then $u < n$, resulting in a positive value for Z. In such circumstances, increasing variability has the effect of making Z smaller, and representative of a greater probability of meeting the subsistence threshold.

Consequently, the Z-score model provides an *expected energy budget rule* (Winterhalder et al., 1999) that predicts that foragers enjoying a positive energy budget should seek to minimize variability (risk-averse behaviors), while those suffering negative energy budgets should seek to maximize variability (risk-prone behaviors). Risk-averse foragers minimize variability in foraging outcomes by adopting behaviors with more certain, but sometimes, less profitable outcomes (Fig. 4). Such behaviors can take several forms and include shifts in mobility, pooling and sharing resources, and storage (Goland, 1991; Grove, 2010; Kaplan et al., 1990; Morgan, 2009, 2012). In contrast, since they are already unable to achieve the necessary foraging returns, risk-prone foragers will take a chance on far less predictable options, but with the potential for achieving foraging returns high enough to boost them over the minimum subsistence threshold. Such circumstances appear rare for human foragers (see Winterhalder et al., 1999 and case studies therein). This observation likely results from the wide range of behavioral options available to humans, such as mobility, that can obviate circumstances leading to risk-prone behaviors. In either case, the predicted response, whether risk-prone or risk-averse, results in a smaller Z-score and minimizes risk.

3. A Z-score model for the Snake River Plain

Viewing storage within the context of the Z-score model requires demonstrating that SRP foragers enjoyed positive energy budgets. In other words, would they have been risk prone or risk averse, since risk-averse foragers are those the model predicts would exploit a risk-minimizing strategy such as storage. Doing so requires information on the subsistence threshold for SRP foragers, as well as data on the mean rates of and variability in returns for the local foraging environment. To provide estimates for such information, we turn to a series of simulated datasets to model how people might respond to environmentally driven shifts in the means and standard deviations for foraging outcomes on the SRP. Such a tack allows us not to predict the specific caloric thresholds at which storage makes sense, but instead to make broader, qualitative predictions about when we might expect to see SRP foragers turn to an adaptation such as storage in response to environmental change.

To evaluate the relationship between energy budget and risk-management strategies, we compare simulated foraging return rates for a suite of SRP prey animals against a hypothetical minimum daily caloric requirement. We use the mean daily caloric intake for the nine recent foraging groups documented in Kelly (2013, Tables 3–5), 2503 kcal/day for an adult, as our minimum subsistence requirement for a single adult. We set foraging time to 6.81 h/day based on the average foraging time for the groups summarized by Binford (2001, Tables 7.11 and 7.12). These numbers suggest that an average hunter-gatherer would require a return rate of about 368 kcal/h to survive. Foragers also provision the caloric needs of group members too young, too old, or too infirm to forage for themselves. Accordingly, we multiply the return rate of 368 kcal/h by Binford's (2001, Table 7.07) mean dependency ratio of 1.68 individuals to arrive at a value of 618 kcal/h, as a higher and more conservative estimate for a

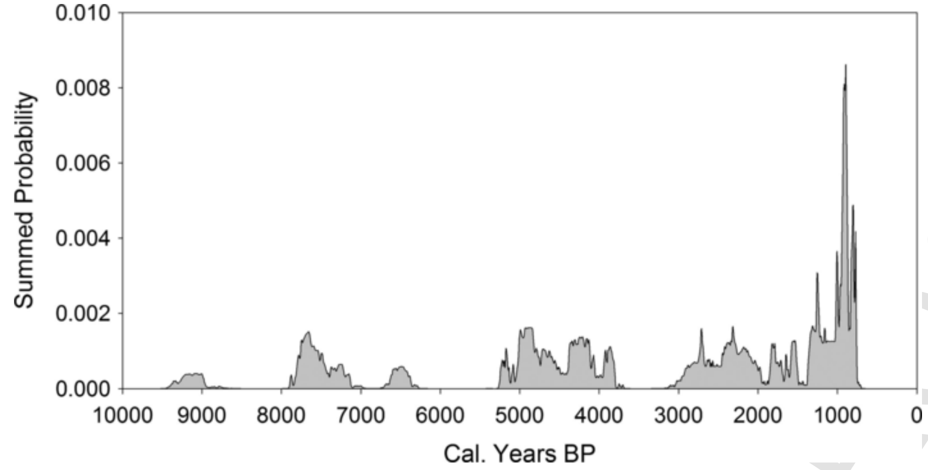

Fig. 2. Cold storage cave radiocarbon dates displayed as a summed probability distribution.

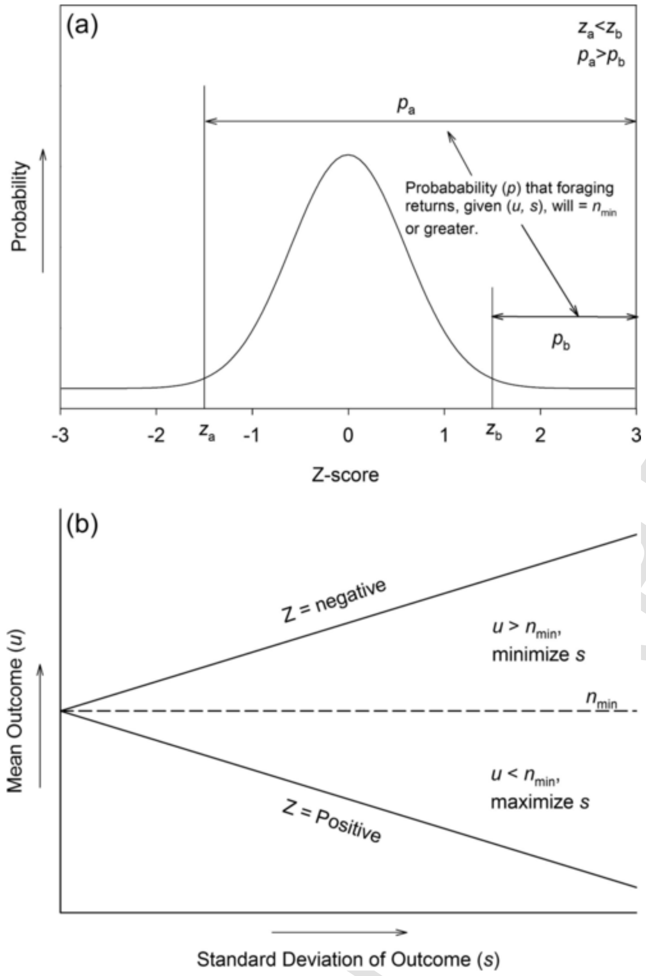

Fig. 3. The Z-score model: (a) Relationship between survival threshold, expected outcome and Z-score; (b) circumstances under which a forager would chose to either minimize or maximize variability in their effort to ensure reaching a subsistence threshold (n_{min}). Here Z represents the slope of a line defined by the equation $u = n - Z * s$. Expressed this way, the Z-score model predicts that a risk-minimizing forager will target the choice with the mean and standard deviation pair describing a line with the greatest slope or in this case, smallest Z value (Winterhalder et al., 1999: 307).

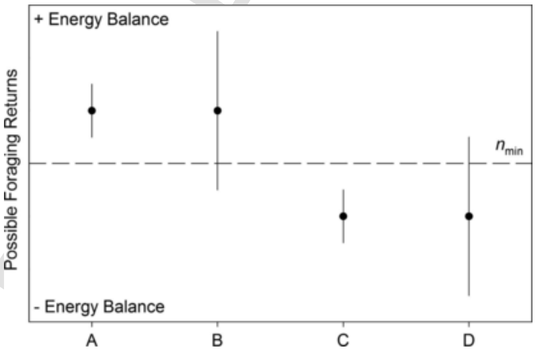

Fig. 4. Four potential subsistence scenarios each displayed with means (dots) and standard deviations (bars) for potential outcomes relative to a survival threshold n_{min}. Scenario A represents a foraging environment providing mean returns above the survival threshold and with limited variability. Scenario B represents circumstances providing mean returns above the survival threshold but associated with high variability. Scenario B would prompt for risk-averse behaviors designed to shift the distribution to look more like A. Scenario C represents circumstances providing mean returns below the survival threshold but associated with little variability. Scenario D represents circumstances providing mean returns above the survival threshold but associated with high variability. Foragers characterized by Scenario C would engage in behaviors designed to increase variability as seen in D, in the hope of exceeding the survival threshold.

caloric survival threshold on the SRP. Return rates for SRP resources (Table 2) were calculated using the data presented in Byers and Ugan (2005, Table 7), with the exception of bison, whose values were adjusted downward by 50% to match those in Henrikson (2004).

We compare the modeled return rates with the survival thresholds identified above. In this instance, a forager subsisting only on bison would expect an average return rate of 842 kcal/h, while an individual targeting prey ranging from bison, deer and pronghorn to smaller prey such as lagomorphs and sage grouse could achieve an overall return rate of almost 3000 kcal/h. In either case, the average foraging return rate exceeds the survival threshold. Thus, our simulated data suggest that SRP foragers would have pursued risk-averse behaviors designed to maximize mean returns and minimize their variability.

Scenario B in Fig. 4 displays the situation where mean returns surpass the survival threshold, but also with highly variable outcomes leading to times when returns might fall below the minimum subsistence requirements. Such circumstances would favor strategies that either move the mean and consequently the entire distribution or reduce the variability in potential outcomes. Storing bison products

Table 2
Snake River Plain diet breadth.

Resource	Scientific name	Energy (kcal/kg)	Live weight (kg/ind)	Edible fraction	Edible weight (kg/ind)	Total (kcal)	Handling time (h)	Handling time (h/kg)	Encounter rate (ind/h)	Encounter rate (kg/h)	Return rate on-encounter (kcal/h)	Overall return rate (kcal/h)
Bison	*Bison bison*	1090	600.00	0.60	360.00	392,400	9.739	0.0271	0.00439	1.5786	40,291.61	842
Deer	*Odocoileus hemionus*	1200	85.00	0.60	51.00	61,200	2.517	0.0493	0.01899	0.9685	24,317.88	1379
Mtn Sheep	*Ovis candensis*	1200	75.00	0.60	45.00	54,000	2.517	0.0559	0.02086	0.9387	21,456.95	1871
Pronghorn	*Antilocapra americana*	1140	56.50	0.60	33.90	38,646	2.017	0.0595	0.02580	0.8745	19,163.31	2281
Hare	*Lepus* sp.	1140	2.42	0.60	1.45	1655	0.125	0.0861	0.27399	0.3978	13,242.24	2449
Cottontail	*Sylvilagus* sp.	1140	1.10	0.60	0.66	752	0.083	0.1263	0.49494	0.3267	9028.80	2569
Squirrel	*Spermophilus* sp.	1200	0.35	0.85	0.30	357	0.058	0.1961	1.16827	0.3476	6120.00	2672
Sage grouse	*Centrocercus urophasianus*	1340	1.50	0.70	1.05	1407	0.258	0.2460	0.81250	0.8531	5446.45	2901

(1) Caloric values are taken from USDA Poultry Products; Lamb, Veal, & Game; Ethnic Foods.

(2) Bison weights and handling times are from Henrikson (2004).

(3) All other handling times were computed using median times from Simms (1987); sage grouse use estimated times for ducks.

(4) Encounter rates for rodents, rabbits, hares, and ungulates use data from Simms (1987). Log density in individuals per square kilometer is $4.33 - 0.75 * \ln(\text{mass in kg})$. Encounter rates are computed as (density ∗ ScaleFactor).

(5) Encounter rates for birds use the data from Simms. Because they cannot use the same allometric equations as mammals, these values are adjusted up or down to reflect changes in encounter rate relative to a base scale factor of 0.0035.

(6) Overall return rates are computed using encounter rate scale factors of 0.0035 and 0.007. Given the first value, encounter rates with all medium artiodactyls (in kg/h) are equivalent to the maximum levels estimated by Simms (1987), yet animals as small as small squirrels should be in the diet.

would be one strategy to do so. While this model lays out circumstances when storage makes sense, namely those with either higher variability in foraging return rates or those with fundamentally lower mean foraging returns, it does not identify the specific external circumstances that may have motivated storage behavior.

On the SRP, the most likely factor conditioning such decisions relative to bison as a food resource would have been climate driven fluctuations in environmental productivity. Although we have no way to document predictability or variability in bison encounters, we suggest that it is reasonable to expect that predictability fell and variability in outcomes increased during times when bison were less common on the landscape. In statistical terms, this is simply a case of as sample size decreases, variability increases. To better understand how such a relationship might operate, we next turn to documenting trends in Holocene climate on the SRP.

4. Holocene environment variability on the Snake River Plain

Viewing the relationships between climate and adaptations such as storage requires fine-grained, regional-scale datasets representing environmental variables most likely to condition behavior. Unfortunately, the SRP lacks the types of climate proxy data available in other places, and this is especially so for fine-grained records. Moreover, the few available SRP paleoenvironmental records that do exist, while certainly informative, are nonetheless course-grained, partial and lack the time depth we need to evaluate our model (e.g. Beiswenger, 1991; Bright, 1966; Bright and Davis, 1982; Butler, 1969; Commendador and Finney, in press). To provide point data useful for monitoring the interplay between climate, environmental productivity and hunter-gatherer subsistence decisions, we turn to an archeoclimate model for the Snake River Plain.

The archaeoclimatic model developed by Bryson (1989, 1992) and Bryson and Bryson (1997, 1998, 2000) provides one method for simulating annual temperature and precipitation values for the late Pleistocene and Holocene. Such models are based on global thermodynamic and hydrodynamic patterns and their influence on the earth-atmosphere-hydrosphere-cryosphere system. These relationships in turn force the weather patterns at any time and place. The derivation of an archaeoclimate model uses information on global glacial volume, Milankovitch variations and the modulating effect of volcanic aerosol to produce a heat energy budget for the study period. Trends in these factors are then used to model variability in meridional temperature gradients that are in turn employed to derive the latitude of the jet stream and the locations of the subtropical anticyclones through time. Finally, archaeoclimate models are calibrated with historically recorded data to produce a region-specific simulation of local rainfall and precipitation through time. In this instance, we use a model calibrated to data from American Falls, Idaho (Table 3). Fig. 5a and b displays modeled mean participation and temper-

Table 3
Analytical datasets used in this paper.

Date (cal. yr. BP)	Yearly precip. (mm)	Winter precip. (mm)	Mean temp. (°C)	δ^{13}C	δ^{18}O	Freq. of storage events	Non-storage bison index
500	302	96	7.69	−17.0	14.6	2	0.75
1000	316	100	8.92	−17.0	15.0	5	0.66
1500	305	97	8.53	−17.0	14.7	5	0.50
2000	307	96	7.41	−17.8	13.3	3	0.27
2500	297	93	8.35	−16.3	13.8	4	0.37
3000	302	90	8.24	−13.1	13.6	2	0.60
3500	303	95	8.18	−15.3	13.2	2	0.42
4000	282	91	8.00	−15.3	13.5	3	0.34
4500	275	91	8.51	−14.6	13.6	6	0.04
5000	277	93	8.39	−14.6	13.7	5	0.04
5500	293	92	8.44	−14.6	14.0	3	0.04
6000	292	100	8.69	n/d[a]	n/d	1	0.04
6500	306	99	8.76	−18.4	14.5	1	n/d
7000	328	110	8.64	−18.4	15.1	2	1.00
7500	341	116	7.72	n/d	n/d	2	0.67
8000	355	118	6.95	n/d	n/d	2	0.67
8500	372	119	6.51	n/d	n/d	1	0.72
9000	352	119	6.69	n/d	n/d	1	1.00
9500	349	119	6.83	n/d	n/d	1	1.00
10,000	370	119	6.48	n/d	n/d	0	1.00

[a] No data.

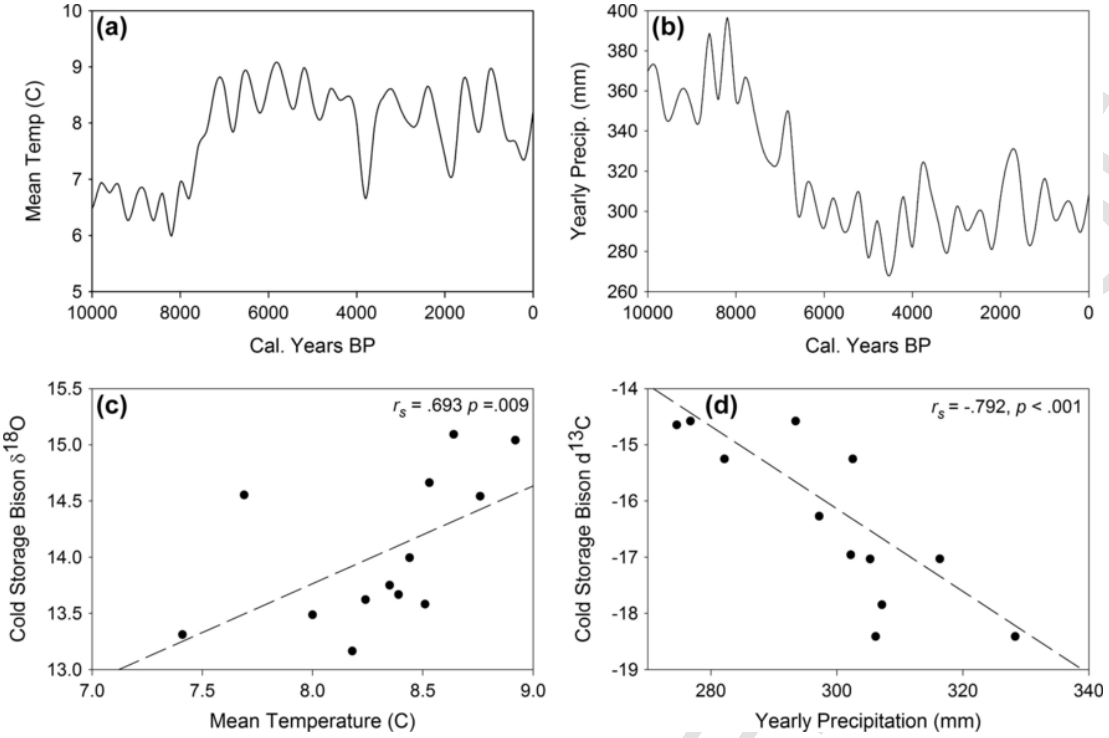

Fig. 5. Snake River Plain environmental relationships: (a) yearly total Holocene precipitation; (b) yearly mean Holocene temperature; (c) relationship between cold-storage bison $\delta^{13}C$ data and modeled yearly precipitation values; (d) relationship between cold-storage bison $\delta^{18}O$ data and modeled yearly temperature values.

ature values plotted at 200-year intervals and this plot documents notable variability in both measures. We focus here on understanding how such variability might ripple through the environmental system and, ultimately, condition storage decisions.

Before using this simulation to evaluate trends in the archaeological record, we first compare it with two non-simulated environmental proxies, stable carbon and oxygen isotope data derived from bison remains from cold storage contexts (Table 4). We do so as a method for "ground-truthing" the simulated data. Because a number of chemical processes related to environmental conditions discriminate against the heavy isotopes of carbon (^{13}C) and oxygen (^{18}O), the resulting levels of fractionation can provide information about the environment. These values are passed up the food chain leaving a diagnostic signature in the tissues of consumers and will reflect the environments they forage across.

In terrestrial contexts, $\delta^{13}C$ values can monitor the proportions of C3 and C4 plants in a consumer's diet, with C3 plant $\delta^{13}C$ values well depleted relative to those of C4 plants. C3 plants include trees, most shrubs, herbs, and many grasses (Ehleringer and Cerling, 2001; O'Leary, 1988). These include cool/moist climate grasses that would have been attractive to bison. In contrast, C4 plants include warm/dry climate grasses and have $\delta^{13}C$ values that are enriched relative to those from C3 plants. Given this knowledge, samples with relatively enriched $\delta^{13}C$ values document warmer/dryer times, while those with relatively depleted values document the converse. We use these data to monitor trends in SRP precipitation across the Holocene.

Oxygen stable isotope analysis employs the relative abundance of ^{18}O to ^{16}O in bone hydroxyapatite to monitor the temperature of water consumed over an animal's life (Fricke and O'Neil, 1996; Genoni et al., 1998; Stephan, 2000). In temperate and boreal regions, mean annual temperature and mean annual meteoric water $\delta^{18}O$ values show a strong positive correlation, with more enriched $\delta^{18}O$ numbers indicating warmer temperatures and depleted values documenting cooler times. Much like $\delta^{13}C$, we use these data to monitor trends in SRP temperature across the Holocene.

The archeoclimate model presents data at 200 year intervals, while the stable isotope data associate with specific dates. To compare the two, we created a running average of the $\delta^{13}C$ and $\delta^{18}O$ data binned in 1000-year periods that increment every 500 years. Any date whose two sigma range fell within a bin was included in the related mean. While we would prefer smaller bin sizes, given the available data, we were unable to create narrower analytical units. The cold-storage cave $\delta^{18}O$ values were arrayed against the mean temperatures predicted by the archaeoclimate model (Fig. 5c). This comparison results in a positive and significant correlation ($r_s = 0.693$, $p = 0.009$), indicating that the modeled temperature data are consisted with the expected relationship between $\delta^{18}O$ and temperature. A similar comparison between yearly, simulated participation values and the $\delta^{13}C$ data results in a strong negative correlation ($r_s = -0.792$, $p < 0.001$), indicating that, as expected, more depleted, C3 carbon values representing forage environments dominated by mesic-adapted plants associate with the predicted periods of higher precipitation (Fig. 5d). Given these results, we feel confident that the simulated data portrays the general trends in SRP climate and move forward by next comparing these patterns with prey abundance data to illustrate what we suggest are the motivations behind hunter-gatherer storage on the SRP.

5. Climate change and bison encounter rates

If the storage of bison products represents an adaptation to shifts in environmental productivity, then this behavior should occur during times of lower or increasingly variable bison encounter rates. To explore this expectation, we next array the environmental trends predicted by the SRP archaeoclimate model against zooarchaeological

Table 4
Cold storage cave stable isotope data. All values derived from bison remains.

Sample ID	$\delta^{13}C$	$\delta^{18}O$	Calibrated date BP	Specimen
10BM56-466	−9.5	18.4	2960–2780	*B. bison* left distal ulna
10BM56-501	−16.7	10.9	2960–2780	*B. bison* long bone shaft
10LN74-141	−10.1	21.1	963–1187	*B. bison* proximal left ulna
10LN74-142	−17.7	n/a	1052–1292	*B. bison* proximal right radius
10LN74-148	−18.4	8.9	963–1187	*B. bison* proximal right radius
10LN74-15.1	−18.9	11.2	2340–2150	*B. bison* proximal right tibia
10LN74-173	−18.4	13.0	2460–2330	*B. bison* right proximal scapula
10LN74-244	−18.3	11.5	2351–2115	*B. bison* right proximal scapula
10LN74-251	−15.8	16.1	2208–2344	*B. bison* right distal mandible frag.
10MA143-134	−18.4	7.9	6740–6600	*B. bison* thoracic vert.
10MA143-3	−17.4	12.1	5290–4880	*B. bison* proximal left ulna
10MA143-34	−14.4	13.5	5290–4880	*B. bison* proximal rib frag.
10MA143-41	−14.7	13.6	5290–4880	*B. bison* horn core
10MA143-48	−9.0	19.3	5290–4880	*B. bison* proximal left scapula frag.
10MA143-55	−14.0	22.2	5290–4880	*B. bison* distal humerus
10MA1435-81	−20.3	14.9	5290–4880	*B. bison* proximal left radius
10MA143-59.1	−20.0	14.2	5290–4880	*C. canadensis* astragalus
10MA143-59.2	−15.9	11.9	5290–4880	*C. canadensis* thoracic vert.
10MA143-70	−15.6	14.1	5290–4880	*B. bison* proximal rib frag.
10PR641-320	−19.0	17.9	1060–920	*B. bison* proximal right ulna
10PR641-388	−18.1	12.1	950–780	*B. bison* cervical vert.
10PR641-434	−18.8	13.9	1050–920	*B. bison* left acetabulum frag.
10PR641-463	−18.2	n/a	1050–920	*B. bison* proximal left ulna
10PR641-508	−15.3	14.2	4060–3830	*B. bison* distal right tibia
10PR641-566	−15.6	13.3	960–790	*B. bison* distal right radius
10PR641-303	−18.7	n/a	957–891	*B. bison* proximal left scapula frag.
10PR641-382	−15.7	n/a	963–890	*B. bison* proximal left scapula frag.

measures of bison abundance to understand trends in prey availability and how they might motivate the adoption of storage.

Empirical research documenting artiodactyl reproduction and recruitment in western North America indicates that variation in temperature and precipitation both condition the reproductive success and, subsequently, the population histories of bison and the other artiodactyl species inhabiting the SRP (Howell et al., 2002; Peek et al., 2002; Picton, 1984; Singer et al., 1997; Van Vuren and Bray, 1986). The primary links between artiodactyl population growth and climate patterns stem largely from the positive correlation between forage quality and precipitation (e.g. Douglas, 2001; Murphy, 1970). The availability of high-quality forage, in turn, influences maternal condition, initial offspring survival, birth weight, growth rate, survival through the first winter, resistance to disease, overall recruitment rates and, ultimately, herd size (Byers and Hogg, 1995; Douglas, 2001; Fairbanks, 1993; Fox et al., 2000; Leslie and Douglas, 1979; Peek et al., 2002; Stephenson et al., 1985). The availability of high-quality forage also impacts the extent that artiodactyls require free drinking water. In times of drought, low-quality forage containing little water can tether groups of animals to scarce free water sources and eventually restrict herd size (Bailey, 1990; McCartney and Miller, 1998; Smith and Krausman, 1988; Van Dyke et al., 1983).

Several studies document the positive effects of cool and moist weather and the strong negative effects of hot and dry conditions on the reproductive success of artiodactyl species in a variety of contexts across the arid West of North America (Brown et al., 2003; Byers and Hogg, 1995; Douglas, 2001; Frank and McNaughton, 1992; Kitchen and O'Gara, 1982; Longhurst et al., 1979; Van Vuren and Bray, 1986). Moreover, these same relationships have also been documented in paleoecological and archaeological contexts from both southwest Wyoming and the Great Basin (Broughton et al., 2008; Byers and Broughton, 2004; Byers and Smith, 2007; Byers et al., 2005). In sum, artiodactyls, bison and otherwise, should be more common during cooler and moister periods during the Holocene.

Understanding the relationships between climate, forage quality and bison abundances allows us to predict how such trends might condition risk-management strategies. Falling environmental productivity should lead to a decrease in bison numbers and, consequently, a decrease in the mean outcome for bison hunting. At the same time, falling numbers of bison would have increased the variance in encounters with these animals. In the case of the SRP, lower precipitation levels, especially in winter, would have dramatically affected both the amount of ephemeral water available later in the season and forage quality on the open steppe of the SRP (Henrikson, 2002), in turn reducing the frequency of and increasing the variability in bison encounters.

To measure bison abundances, we construct a simple prey model-based bison index, that measures bison abundances relative to those of medium artiodactyls such as mule deer (*Odocoileus hemionus*) and pronghorn (*Antilocapra americana*) (cf. Byers and Smith, 2007; Smith et al., 2008). Since bison are primarily grazers and medium artiodactyls such as deer and pronghorn focus on browse, and grasslands are more sensitive to aridity than brushier vegetation communities, bison should have been relatively more common during cooler, moister periods and rarer when it was warmer and dryer (Byers and Smith, 2007). A bison index (bison/all artiodactyls) was created for each of 28 dated and non-cold storage SRP components that include artiodactyl remains of some kind (Table 5). These data were then used to construct a running average as outlined previously.

Fig. 6a arrays our bison index against the yearly precipitation totals generated by the archaeoclimate model. In this case, there is a positive relationship ($r_s = 0.824$, $p < 0.001$) between the two datasets, suggesting that bison were more numerous during moister periods. Comparing winter precipitation, in this case the moisture sum of December, January, February and March, against the bison index also results in a positive relationship between the two variables ($r_s = 0.746$, $p < 0.001$), underscoring the importance of winter moisture to SRP ecosystems (Fig. 6b). The bison index also correlates with the mean yearly temperature values generated by the archaeoclimate model. In this case, there is a negative, significant relationship between the two datasets ($r_s = -0.542$, $p = 0.017$), suggesting that bison were less numerous during warmer periods (Fig. 6c). In sum, these relationships suggest that bison were more common on the SRP during cooler, moister periods. If bison were an important resource to foragers in the region, and the local archaeological record suggests that this was indeed the case, then we might expect to see storage occurring more frequently during warmer, dryer periods when fewer bison were likely to have been available and encounter rates with them less predictable.

6. Cold storage and environmental trends

The cold storage contexts explored here all occur within the pahoehoe and a'a basalt flows covering much of the eastern portion of the SRP (Greeley and King, 1977). These sites consist of lava tubes maintaining year-round ambient temperatures at or below freezing and sustain ice accumulations and/or frozen sediment deposits. Our study focuses on the faunal remains and radiocarbon data from Alpha, Black Widow, Bobcat, Fortress, Scaredy Cat and Tomcat

Table 5
Snake River Plain faunal data from noncold storage contexts.

Site #	Site name		Cal yr. B.P.	*Bison*[a]	*Antilocapra*	*Cervus*	*Odocoileus*	*Ovis*	Bison index[b]	Reference
10OA0210	Rock Springs	Bed 1	0–353	154	15				0.9	Walker (2002)
10CR0526R		1	0–558	2				1	0.67	Chatters (1982)
10OA0210	Rock Springs	Bed 2	228–512	304	32		2		0.9	Walker (2002)
10OA0210	Rock Springs	Bed 3	274–554	495	41	1	1		0.92	Walker (2002)
	Wilson Butte Cave	Stratum A	182–734	28					1	Gruhn (1961)
10GG0001	Bliss (1)		363–843	3	28	23	175		0.01	Plew (1981)
10GG0191	Crutchfield (Hagerman Valley)	Assemblages 1 and 2	512–744	21			17	6	0.48	Murphey and Crutchfield (1985)
10BN0389	The Roasting Rock Site	2005 test excavations	527–751	4					1	Henrikson et al. (2006)
10OA0210	Rock Springs	Bed 4	533–797	169	17		1		0.9	Walker (2002)
10OA0210	Rock Springs	Bed 7	679–835	17	1				0.94	Walker (2002)
10CL0010	Bison Rockshelter	Phase VI	788–1104	153	2		27	31	0.72	Swanson (1972)
10CL0003	Veratic Rockshelter	Phase VI	788–1104	319	7	2	5	39	0.86	Swanson (1972)
10BK0026	Wahmuza	A VI (includes DW1)	933–1413	6			15		0.29	Holmer and Ringe (1986)
10CR0197	Quill Cave	Stratum 2	995–1363	364				10	0.97	Butler (1971)
10BK0026	Wahmuza	A V	1183–1419	1	33		67		0.01	Holmer and Ringe (1986)
10CR0334		Soils 1–5	1477–1829	23	44			75	0.16	Chatters (1982)
10BK0026	Wahmuza	A IV	1722–2006	1	8		38		0.02	Holmer and Ringe (1986)
	Wilson Butte Cave	Stratum B	1644–2324	37	2				0.95	Gruhn (1961)
10FR0005	Standing Rock Overhang	1–200 cm	2038–2334	4		2		193	0.02	Miller (2008)
10GG0191	Crutchfield (Hagerman Valley)	Assemblage 3	2265–2797	2	3		5		0.2	Murphey and Crutchfield (1985)
10CL0003	Veratic Rockshelter	Phase III	2770–3406	128	6	1	4	59	0.65	Swanson (1972)
10CL0010	Bison Rockshelter	Phase III	3112–3640	32			1	1	0.94	Swanson (1972)
10FR004	Weston Canyon Rockshelter	1996 excavations	3506–3826	9				177	0.05	Miller (1999)
10CL0003	Veratic Rockshelter	Phase II	3980–5660	7	22		11	136	0.04	Swanson (1972)
	Wilson Butte Cave	Stratum C Upper	7183–8239	13					1	Gruhn (1961)
10FR004	Weston Canyon Rockshelter	1969 excavations: Layers 17-12	7672–8520	1		4		44	0.02	Miller (1972)
10BV0030	The Wasden Site	Layer 16	7726–8882	50[c]					1	Butler (1971)
10CL0010	Bison Rockshelter	Phase I	8597–11,065	7					1	Swanson (1972)

[a] All counts presented as Number of Identified Specimens (NISP).

[b] Bison index calculated as (bison)/(all artiodactyls).

[c] The Wasden Site is reported only as a count of individuals. However, only bison are reported for this occupation and we assign it a bison index value of 1.0.

Caves (Henrikson, 2003). Each of these caves has produced similar assemblages consisting of antler tines digging tools, broken hand/hammer stones, *Artemisia* sp. stalk storage features and bison skeletal material. In some instances, the *Artemisia* remains were directly located in buried contexts overlying deposits of clear ice and in several more the plant materials were associated with the bison remains, suggesting their use as a lining or protective cover for stored bison products.

Radiocarbon data from these caves (Table 1, Fig. 2) suggest that they were used episodically across the Holocene, as early as 9460 cal. years BP, and, as stated above, we suggest their use reflects a response to environmentally driven resource scarcity. To unpack the relationships between environmental change and storage, we created a measure of dated cold-storage events by using a running tally of sites binned in 1000 year intervals, incremented every 500 years. In this case, one storage event would represent a set of dates that all overlap at two sigma and are from a single cold-storage context. The pooled dates for the storage events was used for temporal control. Our sample includes 34 dates from the six dated cold storage caves. With two exceptions, these dates all derive directly from bison skeletal remains, *Artemisia* sp. stalk fragments that line storage features or antler tine digging implements found associated with the storage features. While this is admittedly a coarse measure, here again the bin size was the smallest available given the limited dataset.

Fig. 6d displays the relationship between storage frequency and yearly precipitation. In this case, there is a negative and significant relationship ($r_s = -0.606$, $p = 0.005$) between the two datasets and this pattern suggests that SRP foragers resorted to storage less frequently during moister periods. Comparing winter precipitation against the frequency of cold-storage events also results in a significant relationship ($r_s = -0.673$, $p = 0.001$; Fig. 6e). Storage and mean temperature also associate. As can be seen (Fig. 6f), these two datasets correlate positively and significantly ($r_s = 0.479$, $p = 0.033$), indicating that SRP foragers employed storage more frequently during warmer times. Taken together the relationships between temperature and precipitation, as well as both artiodactyl abundances and storage frequency, support our main hypothesis.

As a final test of our model, we compare the frequency of storage events with the bison abundances from non-storage contexts (Fig. 7), with the expectation that the two datasets will demonstrate a negative relationship. As predicted, this comparison results in a significant negative correlation ($r_s = -0.635$, $p = 0.004$). This relationship suggests that when cold-storage bison remains dominate SRP archaeofaunas, these animals were otherwise less common in the archaeological record. Conversely, bison enjoy greater representation in non-storage archaeofaunas when cold storage events are rare. This relationship is just what one would expect if foragers stored bison products during times when this important resource was rare on the landscape or encounters with it unpredictable.

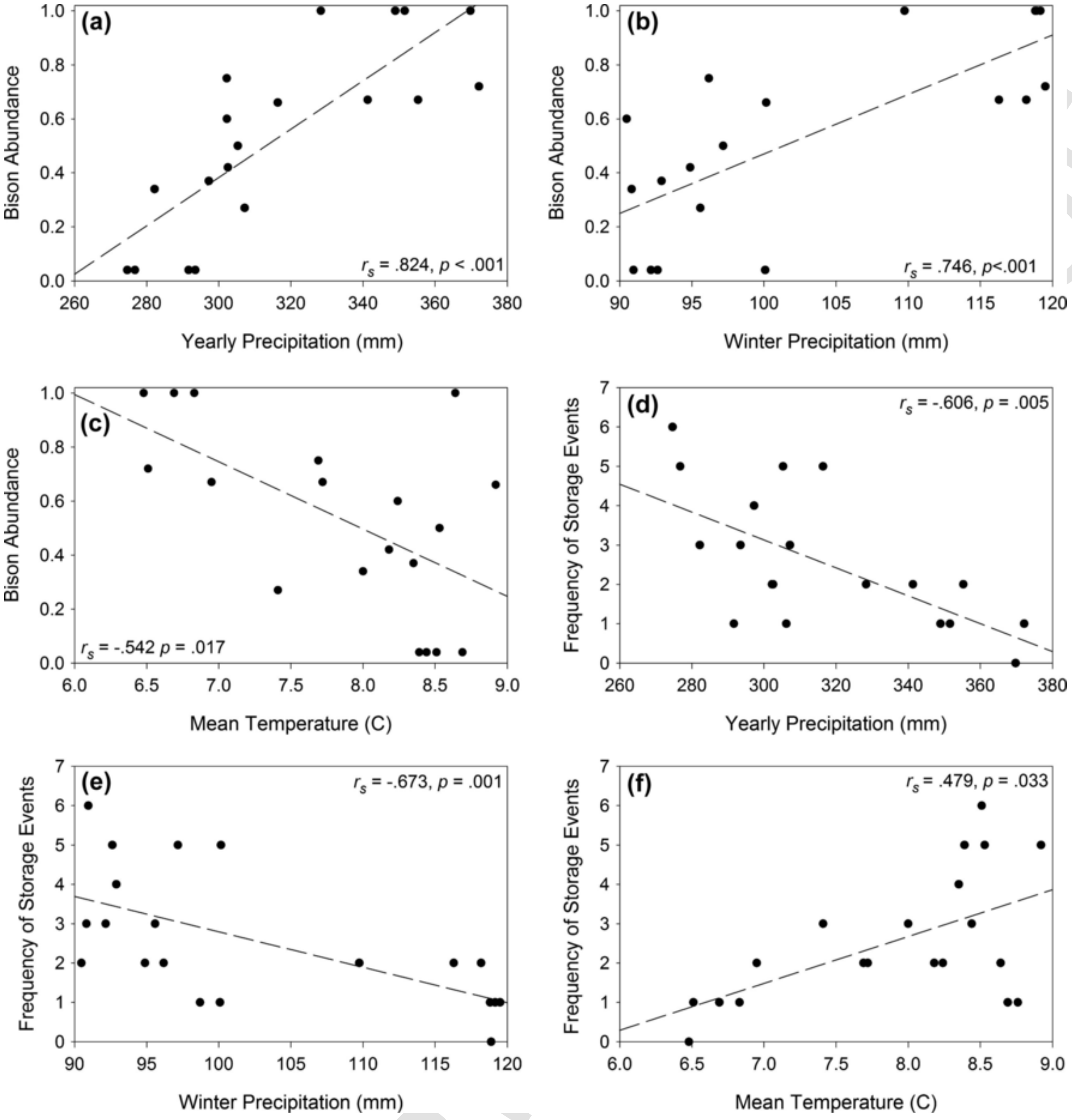

Fig. 6. Relationships between Snake River Plain climate variables, bison abundances and storage frequency: (a) bison index and modeled yearly Holocene precipitation; (b) bison index and modeled Holocene winter precipitation; (c) bison index and modeled mean Holocene temperature; (d) cold-storage events and modeled yearly Holocene precipitation; (e) cold-storage events and modeled Holocene winter precipitation; (f) cold-storage events and modeled mean Holocene temperature.

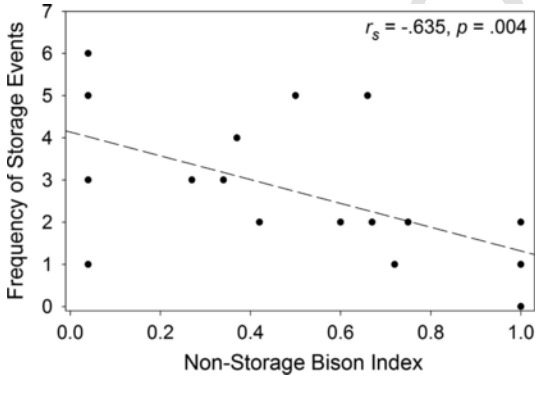

Fig. 7. Relationship between frequency of cold-storage events and the SRP bison index for non-cold storage contexts.

7. Storage, macronutrients and overwintering on the Snake River Plain

Our study has shown that the use of cold SRP lava tubes for storage appears to be a response to environmentally driven declines in bison numbers leading to increasingly variable encounters with these animals, even as early as 9000 yr. B.P. Such periods also appear to have been those less favorable to bison, likely driving down both the frequency and predictability of encounters with these important prey animals. So far, however, our model has not addressed the impact of intra-annual seasonality on subsistence decisions, a factor suggested by others to mediate bison storage on the SRP (Gould and Plew, 1996; Henrikson, 2002, 2003; Plew, 1990, 2003, 2005). Even during multi-year periods of environmental stress, the warmer months would have likely been a time of more reliable, predictable and less variable returns, as long as winter precipitation was sufficient to both produce high-quality forage and fill ephemeral ponds, prompting bison to migrate to the SRP from winter ranges to the south and east. Obviously, achieving the necessary return rate thresholds during the winter would be much more difficult and variable than during summer.

If the risk-mitigation model developed here accurately identifies the motivation behind bison storage, while at the same time, there is a seasonal component to this practice on the SRP, then we also expect that the cold storage record will document carcass parts most useful within the context of over-wintering. Annual fluctuations in fat availability, for example, can impose nutritional constraints on foragers, resulting in a focus on fatty foods in times of resource stress. Following Brink (1997), Henrikson (2003) argues that infrequent small-scale encounters with bison prompted people to maximize skeletal fat recovery. Recent investigations at Baker Cave, Idaho, support this picture of bison use on the SRP (Breslawski, 2014; Breslawski and Byers, 2015). Unlike Henrikson's (1996, 2002, 2003, 2004) findings at cold-storage sites, Baker Cave did not contain evidence of storage features. Rather, it appears that hunters procured bison at a distance from Baker Cave during the late winter/early spring and transported them to the site for later processing and consumption. Moreover, several indicators of processing intensity derived from the Baker Cave bison remains all point to the acquisition of skeletal fat as an important activity. The Baker Cave example suggests a motivation behind cold storage features: the need to store fatty resources for seasonal periods of fat scarcity. To test this prediction, we next compare the cold storage cave skeletal element profiles with measures of both overall (meat and fat) and marrow specific utilities for bison carcass portions.

Clearly, one important resource likely stored in these cold-storage caves would have been the meat attached to the cached skeletal parts, and we do not doubt that meat was an important component of the storage strategy. However, a comparison of Emerson's Total Products Index (Emerson, 1990) with minimum number of elements (MNE) values representing an aggregate of the skeletal element values from the three best documented cold storage faunal assemblages (Table 6), Scaredy Cat, Bobcat and Tomcat caves (Henrikson, 2003), fails to correlate significantly ($r_s = 0.357$, $p = 0.243$). This result suggests that combined meat, fat and protein utility, by itself, did not condition the selection or transport of skeletal parts into these sites. This is not necessarily surprising. Ethnographic accounts demonstrate that hunters often field strip meat from bone, effectively dividing bone and soft tissues into two, different transportable resources (e.g., Bunn et al., 1988; O'Connell et al., 1988, 1992). This observation, however, begs the question, why transport bone into the cold, dangerous, pitch-black spaces that typify SRP lava tubes? We suggest that the answer rests in the fat content of the bones themselves.

Table 6
Cold storage cave faunal data.

Element	Minimum number of elements by site				UMI[a]	Total products[b]
	Bobcat	Scardy Cat	Tomcat	Total MNE		
Horn core	1	1		2		
Cranium		1		1		14.2
Mandible			2	2		14.2
Rib	9	15	9	33		100
Scapula		2	5	7		31.6
Humerus	1		2	3	22.8	28.4
Innominate	1			1		54.7
Metapodial	2	2		4	33.5	11
Radius	5	1	3	9	26.3	19.7
Ulna	2	1	2	5		19.7
Femur		4		4	34	100
Tibia	5	3	2	10	51.1	58.1
Calcaneus	1	0		1	2.6	
Vertebra	1	2		3		78

[a] Morin (2007).

[b] Emerson (1990).

We use Morin's (2007) Unsaturated Marrow Index (UMI) to evaluate the prediction that skeletal fat conditioned storage decisions. This measure ranks the within-bone unsaturated fat yields for each element within an artiodactyl skeleton. Several researchers have documented the skeletal fat variability found in different artiodactyl species and these studies show that different elements provide varying levels of overall fat utility. Moreover, not all fat is created equal. Morin's (2007) reanalysis of Binford's (1978) Nunamiut data found that fat quality, measured as the proportion of unsaturated fat, mediated processing decisions. If fat utility conditioned SRP cold storage decisions as well, then fat-seeking hunters should have cached fat-rich elements at higher rates than fat-poor ones. Arraying the UMI against the aggregated cold-storage MNE profile results in a correlation between the two measures ($r_s = 0.812$, $p = 0.058$; Fig. 8). Taken together with the results of the long-term relationship between storage and climate, this test suggests that SRP foragers stored bison products in cold storage caves as an overwintering strategy during warmer/dryer periods characterized by both reductions in bison encounter rates and the predictability of such encounters should they occur.

8. Conclusions

Our results support the argument that the relationships between Holocene climatic variability and the density of bison on the SRP provided the prime-mover behind the adoption of cold storage as a risk-sensitive foraging behavior. In this example, storage occurs during dryer, warmer periods, times when bison would have been less common and encounters with them less predictable. Moreover, this study suggests that SRP foragers employed storage as a risk-mitigation strategy in response to both long-term and seasonal variation in bison encounter rates.

Clearly, we need more data to refine the SRP archaeoclimate model, build a more robust archaeological dataset and eventually, more fully evaluate the hypotheses presented here. Such information will be critical to fill the gaps in our current understanding of the reasons behind the use of ice caves on the SRP. For example, additional AMS dates and isotopic analyses of bison and other artiodactyls re-

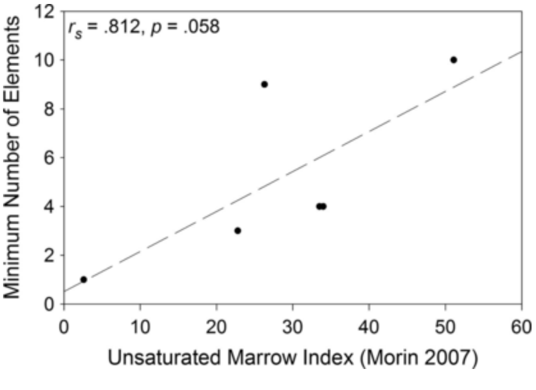

Fig. 8. Relationship between Morin's (2007) Unsaturated Marrow Index and skeletal element frequencies from SRP cold-storage caves.

covered from non-storage sites in the region would help to refine the SRP environmental chronology. Building a broader dataset of well-described faunal assemblages would also help clarify the patterns described in this paper. The strength of any set of conclusions rests on the quality and quantity of the data available to the researcher. In this case, we have identified a set of relationships based on relatively few data points. Consequently, increasing our knowledge of both the composition of SRP open-air archaeofaunas and the make-up of those from the cold storage caves is an important next step to validating our conclusions.

The locations of cold-storage caves represent another important avenue of research requiring future attention. This paper asked the question, when would have storage made sense, while the related issue, where would it make sense to store resources and how do the locations of the cold storage sites articulate with mobility and land use patterns is slated for future research. How these sites fit into prehistoric seasonal rounds, how environmental conditions might have conditioned these mobility patterns and how geography might mediate the relationships between them is an important gap in knowledge for the SRP, but one beyond the scope of this paper.

In conclusion, the storage of frozen bison meat in cold lava tube caves has little resemblance to the types of storage that occurred in other parts of the Intermontane West. Instead, this distinctive technology shares more similarities with the hunting economies of the Subarctic and Northern Plains. Cold lava tubes appear to have allowed a much more extended “shelf-life” for meat caches than the winter snow banks that were relied further north and on the Great Plains, but essentially functioned in the same way (Henrikson, 2002). If viewed in this light, the cold storage caves of southern Idaho were most certainly critical to the seasonal round and helpful to people during lean times, but their isolated, stationary position in a sparse and only seasonally productive environment of the sagebrush steppe (even with its ephemeral ponds) would have greatly influenced their utility. Nonetheless, this investigation of cold storage caves and their influence on human subsistence patterns in southern Idaho contributes toward a more comprehensive understanding of hunter-gather adaptation and the diverse factors that have allowed habitation of the SRP throughout the human occupation of western North America.

Acknowledgements

We thank the Idaho BLM for supporting the cold-storage cave field studies. Steve Simms, Andrew Ugan, Jacob Freeman and two anonymous reviewers provided helpful comments on an earlier draft of this paper. The final result was much improved and we thank them for their input.

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