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Experimental examination of animal trampling effects on artifact movement in dry and water saturated substrates: a test case from South India

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ABSTRACT

This paper presents the motivation, procedures, and results of an experiment that examines short episodes of animal trampling in dry and water saturated substrates in South India. While horizontal artifact displacement was similar to that modeled by other trampling experiments, vertical artifact displacement in water saturated substrates was greater than any reported experiment to date. The toolstone used in this experiment, a silicious limestone, exhibited minimal damage after trampling. Artifact inclination patterning appeared to be a potentially diagnostic middle-range marker of trampling in water saturated substrates. Given the abundant number of Paleolithic sites that are located on flat, open surfaces near water-bodies, or experience monsoonal climatic regimes, we propose that future excavations should measure artifact inclination on a regular basis.

1. Introduction

During archaeological survey work in the Jurreru River Valley, Kurnool District, South India (Fig. 1), team members noticed hardened hoof-prints peppering the valley floor, left over from the previous monsoon season (Fig. 2a). Fresh hoof-prints were also observed along the banks of local streams, where villagers lead livestock daily to fresh water sources (Fig. 2b). The abundance of these marks suggested that stone artifact scatters in seasonally or perennially saturated parts of the valley floor could have been rearranged and possibly damaged by animal hooves in the past. The vertical concavities of some of the hoof-prints we observed were deep enough that they might readily have displaced near-surface buried artifacts. In saturated substrates like these, but where archaeological horizons were embedded, trampling might lead to any number of rearrangements including, but not limited to: (1) the separation of a single archaeological horizon into two; (2) the combination of two archaeological horizons into one; (3) the creation of false buried sites composed entirely of derived artifacts that originated on the surface.

Although the need to study the role of animal trampling in this particular depositional environment was clear enough, it soon occurred to us that it could be of much wider relevance. Actualistic study of trampling in the Jurreru Valley could therefore contribute to a greater understanding of artifact displacement in sites from other regions with highly seasonal rainfall regimes and widely spaced waterpoints that attracted game animals on a daily basis.

It is now generally accepted that post-depositional processes may alter or erase spatial patterns in the archaeological record and may even create artificial ones. It follows that the behavioral interpretation of spatial patterns can only be made *after* the processes that shaped the artifact/ecofact patterning are understood (e.g. Binford, 1983; Schiffer, 1983). Formation Theory (FT) (Shott, 1998) is a form of inference that allows archaeologists to untangle these processes by comparing them, via analogy, to a known reference. FT not only strives to predict the material

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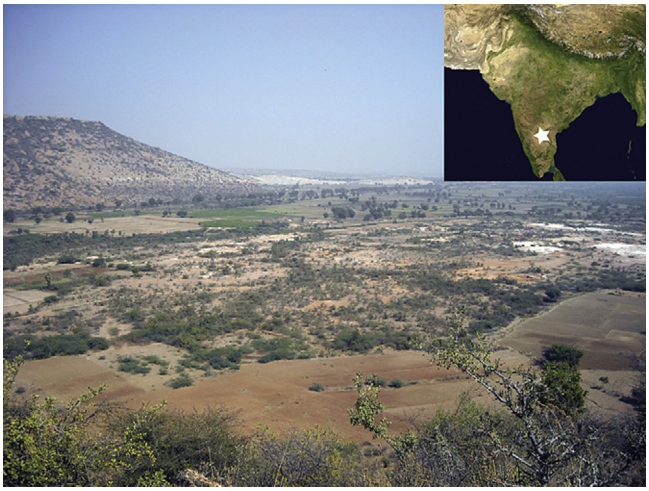

Fig. 1. The Jurreru Valley and its location within the Indian subcontinent.

consequence of human behavior, but seeks to explain how those material consequences become altered between discard and discovery. When the data used to test components of FT (taken from the ethnographic, historic, geologic, and taphonomic records) run out, we resort to controlled replication experiments and actualistic studies.

Artifact trampling experiments fall across the latter two categories of FT testing, and strive to test whether humans and animals can significantly influence the formation of the archaeological record to better understand depositional conditions (e.g. Gifford-Gonzalez et al., 1985; Lopinot and Ray, 2007). Trampling experiments examine three key factors: horizontal displacement of artifacts, their vertical displacement, and artifact damage. Since many variables are implicated in such post-depositional changes (substrate type, trampling agent, artifact material/morphology, time, and trampling intensity) these variables are routinely recorded (e.g. Table 1). The shared goal of all such experiments is to determine the extent to which each variable contributes to the vertical/horizontal displacement of, and damage to, a specific material record.

Here, we present an artifact trampling experiment relevant to much of the Old World, involving mammalian herds trampling upon knapped stone flakes in dry and saturated sediments. The purpose of the experiment is to model, in a controlled setting, trampling as it might occur in regions that experience seasonal rainfall, or sediments on the banks of expanding and contracting water-bodies (i.e. lakes, rivers, streams). As part of this process, we attempt to identify markers that will assist in recognizing whether stone artifacts have been trampled in saturated or dry sediment.

The design of this experiment expands on other published case studies by examining several variables not previously, or rarely, considered or quantified. Firstly, the effects of a saturated versus dry substrate are examined. Secondly, we move the focus away from human trampling to that of two animals of widely differing weights: the water buffalo (*Bubalus bubalis*) and the goat (*Capra aegagrus hircus*). Although likely agents in the alteration of pastoralist settlements, these also serve as preliminary analogs for large and small game animals – suspected agents of post-depositional alteration in many pre-farming contexts (Fiorillo, 1989; Lopinot and Ray, 2007). Our study also differs from most others in that we focus strictly on short trampling episodes rather than the long, accumulative, impact of so many human-agent experiments. We join Behrensmeyer et al. (1986) and Dominguez-Rodrigo et al. (2009) in further exploring the effects of short episodes of animal trampling in open contexts rather than the effects of human foot-traffic in constrained surroundings such as caves or domestic dwellings (e.g. Villa and Courtin, 1983). Furthermore we introduce a silicious limestone as a novel experimental toolstone with different properties and potentials for damage than the flints and obsidians so popular among previous experiments. Finally, we introduce a methodological refinement by recording artifact inclination before and after the experiment. In a saturated substrate we expected that artifact inclination, a trait that potentially preserves archaeologically (Andrews, 2006; Fiorillo, 1989; Pappu and Akhilesh, 2006), would change with trampling, as predicted by Hill and Walker (1972) and Olsen and Shipman (1988: 537).

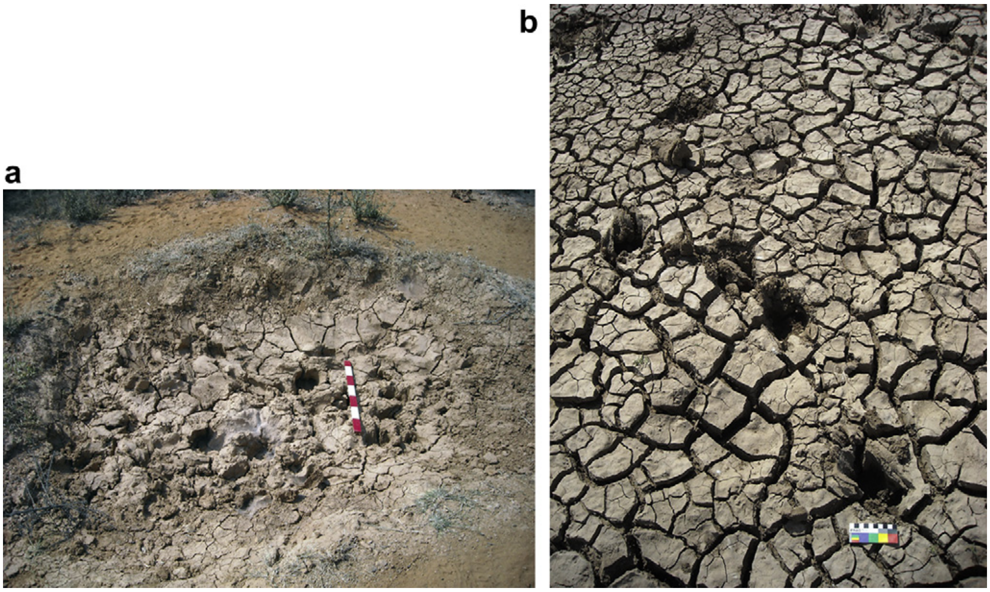

Fig. 2. An example of water buffalo hoof-prints in the Jurreru Valley left over from the previous monsoon season (a) and an example of recently created water buffalo hoof-prints left on the bank of the Jurreru River (b).

Table 1
A compilation of landmark trampling experiments for comparison to the present study. Some trampling experiments are not included here as they may be embedded within larger reports, or only reported casually (e.g. Wilk and Schiffer, 1979).

Reference	Location	Principal Substrate	Dry, Moist, Wet, Saturated	Trampled Artifacts	Trampling Agent	Time/Amount Trampled
Stockton (1973)	Australia	Sand	Dry	Red glass	Humans	1 day
Flenniken and Haggerty (1979)	Northwestern USA	Silt loam	Dry	Obsidian flakes	Humans (soft-soled footwear)	1000 crossings
	Northwestern USA	Alluvial sand	Dry	Obsidian flakes	Humans (soft-soled footwear)	1000 crossings
	Northwestern USA	Clay and gravel	Dry	Obsidian flakes	Humans (soft-soled footwear)	1000 crossings
	Northwestern USA	Basalt gravel	Dry	Obsidian flakes	Humans (soft-soled footwear)	1000 crossings
	Northwestern USA	Obsidian flakes	Dry	Obsidian flakes	Humans (soft-soled footwear)	1000 crossings
Behrensmeyer et al. (1986)	Unspecified natural stream	Coarse sand and gravel	Wet (not quantified)	Bones	Humans (soft-soled footwear)	3 min
Villa and Courtin (1983)	France	Loose, well-sorted silty sand	Dry	Flint flakes, bones, shells, sherds, limestone pebbles	Humans (barefoot or sandals)	16, 22, 32, 36 days
Goerke (1983)	India	Hard packed sand with small pebbles	Dry	Chert and chalcedony flakes	Elephant	25 crossings
Gifford et al. (1985)	California, USA	Compact sandy silt	Dry	Obsidian flakes	Humans (soft-soled footwear)	2 h
	California, USA	Unconsolidated medium fine sand	Dry, but moist below 6–8 cm in depth	Obsidian flakes	Humans (soft-soled footwear)	2 h
Olsen and Shipman (1988)	Unspecified	Pea gravel	Dry	Bones	Humans (barefoot)	2 h
	Unspecified	Coarse sand	Dry	Bones	Humans (barefoot)	2 h
	Unspecified	Fine sand	Dry	Bones	Humans (barefoot)	2 h
	Unspecified	Potting soil	Dry	Bones	Humans (barefoot)	2 h
Pryor (1988)	Unspecified lake shore	Sandy soil	Dry	Obsidian flakes	Humans (soft-soled footwear)	2 h
	New York, USA	Loamy soil	Dry	Obsidian flakes	Humans (soft-soled footwear)	2 h
Fiorillo (1989)	Nebraska, USA	Hard sandy surface	Dry	Bones	Cows	2 weeks
	Nebraska, USA	Wetter, soft substrate covered with vegetation	Wet (not quantified)	Bones	Cows	2 weeks
Nielsen (1991)	Arizona, USA	Muddy gravel	Dry	Bones, obsidian flakes, sherds	Humans (tennis shoes)	1500 crossings
	Arizona, USA	Muddy gravel	Dry	Bones, obsidian flakes, sherds	Humans (tennis shoes)	800 crossings
	Arizona, USA	Muddy gravel	Wet (not quantified)	Bones, obsidian flakes, sherds	Humans (tennis shoes)	800 crossings
	Arizona, USA	Muddy gravel	Dry	Sherds	Humans (tennis shoes)	100, 200, 300, 400, 800 crossings
	Arizona, USA	Muddy gravel	Dry	Sherds	Humans (tennis shoes)	3 days, 6 days
	Arizona, USA	Muddy gravel	Dry	Wood, brick, sherds	Humans (tennis shoes)	1 day
Shea and Klenck (1993)	Massachusetts, USA	Sandy soil	Moist (not quantified)	Brandon flint	Humans (rubber soled shoes)	15 min
	Massachusetts, USA	Sandy soil	Moist (not quantified)	Brandon flint	Humans (rubber soled shoes)	30 min
	Massachusetts, USA	Sandy soil	Moist (not quantified)	Brandon flint	Humans (rubber soled shoes)	45 min
McBrearty et al. (1998)	Connecticut, USA	Low density sand	Dry	Chert flakes	Humans (rubber soled shoes)	1 h
	Connecticut, USA	High density sand	Moist (not quantified)	Chert flakes	Humans (rubber soled shoes)	1 h
	Connecticut, USA	Low density sand	Dry	Obsidian flakes	Humans (rubber soled shoes)	1 h
	Connecticut, USA	High density sand	Moist (not quantified)	Obsidian flakes	Humans (rubber soled shoes)	1 h
	Connecticut, USA	Low density loam	Moist (not quantified)	Chert flakes	Humans (rubber soled shoes)	1 h
	Connecticut, USA	High density loam	Moist (not quantified)	Chert flakes	Humans (rubber soled shoes)	1 h
	Connecticut, USA	Low density loam	Moist (not quantified)	Obsidian flakes	Humans (rubber soled shoes)	1 h
	Connecticut, USA	High density loam	Moist (not quantified)	Obsidian flakes	Humans (rubber soled shoes)	1 h
Lopinot and Ray (2007)	Springfield, Missouri	Gravels	Dry	Gravels	Asian elephants	50 crossings
	Springfield, Missouri	Gravels	Dry	Gravels	Bison	Unknown

Table 1 (*continued*)

Reference	Location	Principal Substrate	Dry, Moist, Wet, Saturated	Trampled Artifacts	Trampling Agent	Time/Amount Trampled
Dominguez-Rodrigo et al. (2009)	Spain	Fine-grain sand	Dry	Bones	Humans (esparto grass soles)	<2 min
	Spain	Medium-grain sand	Dry	Bones	Humans (esparto grass soles)	<2 min
	Spain	Coarse-grain sand	Dry	Bones	Humans (esparto grass soles)	<2 min
	Spain	Sand and clay	Dry	Bones	Humans (esparto grass soles)	<2 min
	Spain	Sand and gravel	Dry	Bones	Humans (esparto grass soles)	<2 min
Present Study	Andhra Pradesh, India	Medium silt, fine sand	Dry	Limestone flakes	Water buffalo	3 min, 24 s
	Andhra Pradesh, India	Medium silt, fine sand	Dry	Limestone flakes	Water buffalo	3 min, 24 s
	Andhra Pradesh, India	Medium silt, fine sand	Saturated (quantified)	Limestone flakes	Goats	3 min 36 s
	Andhra Pradesh, India	Medium silt, fine sand	Saturated (quantified)	Limestone flakes	Goats	3 min 36 s

2. Methods

2.1. Lithic assemblage

M.I.E. knapped 120 stone flakes using hard-hammer discoidal reduction from a dark blue limestone found outcropping in the Jurreru River Valley, and used frequently by local prehistoric inhabitants (Petraglia et al., 2007, 2009). Flake size was variable (Table 2), but to ensure proper controls the flakes were sorted into four groups of 30 by a process of random selection. Two-sample *t*-tests show that each group of 30 flakes is statistically the same in terms of flake mass, length, width, thickness, and the length to width ratio. Following Gifford-Gonzalez et al. (1985), the specimens were painted white on one side to facilitate numbering and field recovery.

2.2. Trampling grid set-up

Four grids were demarcated with wooden stakes in an area of the valley surface that was devoid of prehistoric artifacts. Two of these grids were completely saturated using water from the nearby Jurreru River, while the other two were left dry. It was arranged that the buffalo and goats to be used in the experiment would each trample a saturated grid and a dry grid. The grids designated for the buffalo were 2 m by 2 m, while the grids designated for the goats were 1 m by 1 m.

Thirty experimental stone flakes were placed in each grid, painted side up. The initial location and inclination of each flake was recorded in 3-D space. Elevation (z) was recorded by placing a wooden stake adjacent to each grid, notching the stake, and attaching a string and line-level to the notch. Horizontal location (x, y) was recorded by measuring the distance between each stone flake and the adjacent wooden stake, as well as the magnetic compass direction. The length, width, and thickness of each artifact can be described by three orthogonal axes (the long (a), intermediate (b), and short (c) axes). The inclination of the plane defined by the long and intermediate axes (i.e., the a–b plane) of each artifact was measured using a Brunton compass. Two-sample *t*-tests show there was no statistically significant difference between any of the grids in regards to the initial artifact inclinations.

2.3. The substrate

Particle size analysis was conducted on sediments collected from a series of test pits in each experimental plot using a Malvern Instruments Mastersizer 2000 in the Physical Geography Laboratories, University of Cambridge. Six samples were collected in total, three from the buffalo saturated grid, and three from the goat saturated grid (from the east, center, and west sections). Laser diffraction particle size analysis (LDPSA) offers a rapid, accurate and reproducible method to measure particles ranging from 0.1 to 2000 μm in size (see International Organization for Standardization (ISO) standard, ISO 13320, "Particle size analysis – Laser Diffraction Methods – Part 1: General Principals"). The measurement system consists of a laser light source of fixed wavelength, an observation cell through which sediment grains suspended in a solution of water and (or) dispersing agents are circulated, and an array of detectors to measure scattered light over a wide angle (typically 0.02–140°). Particle size (volume-based) is inferred through inversion of measured scattering from the instrument with model-predicted scattering using Lorenz–Mie scattering theory (e.g., Bohren and Huffman, 1983) in which light scattering angle is inversely proportional to particle size and scattering intensity is proportional to particle volume. For our analyses, we assumed a particle refractive index and absorptivity of 1.6 and 0.1,

Table 2
Descriptive statistics of the mass and dimensions of 120 limestone flakes. All flakes were divided into four groups of 30. Two-sample *t*-tests demonstrated that the mass and dimensions of each group of 30 flakes was statistically similar to that of every other group.

	Mass (g)	Length (mm)	Width (mm)	Thickness (mm)	Length to Width Ratio
Mean	22.11	53.186	37.82	9.60	1.53
Median	17.25	52.63	37.14	9.06	1.39
Standard Deviation	17.41	13.02	11.86	4.08	0.61
Minimum	3.70	27.94	14.50	3.06	0.69
Maximum	91.60	93.10	85.47	24.50	4.20

respectively, and the particle size distributions reported for each sample are an average of 3 measurements, each collected for 20 s. Sediments from all test pits are poorly sorted and particle sizes range from a medium-grained silt to a coarse-grained sand (Table 3).

2.4. Quantifying substrate saturation

The water content of samples was determined by weighing a fixed volume (Table 4) of wet sediment, then drying the sediment and finding the dry weight to determine the water content. Sediments were dried at 40 °C for 6 h, and for a further 6 h at 105 °C to remove all water in the samples.

Volumetric water content, θ, was calculated using the relationship:

$$\theta = \left(m_{\mathrm{wet}} - m_{\mathrm{dry}}\right) \Big/ \left(\rho_{\mathrm{w}} \times V_{\mathrm{b}}\right) \tag{1}$$

where m_{wet} and m_{dry} are the masses of the sample before and after drying in the oven, ρ_{w} is the density of water; and V_{b} is the volume of the sample before drying the sample. Water content, u, is expressed in terms of the mass of water per unit mass of the moist specimen:

$$u = \left(m_{\mathrm{wet}} - m_{\mathrm{dry}}\right) \Big/ m_{\mathrm{wet}} \tag{2}$$

The volumetric water content (θ) fell within the range for a fully saturated sediment (0.2–0.5) (Dingman, 2002; van Genuchten, 1980). Water content in terms of the wet mass was between 3 and 4% (Table 4).

2.5. Trampling experiments

A herd of 17 buffalo trampled their designated dry and saturated grids via six passes, lasting 3 min 24 s in total (Fig. 3). Local workers, as well as field archaeologists, stood on opposite sides of each grid, forming a human barrier to ensure the buffalo were funneled over the grids. Once beyond the grids, the buffalo herd was made to turn around for another trampling pass.

While the buffalo were for the most part cooperative, the goats were not. A herd of 16 goats made eight passes over their saturated and dry grids in 3 min 36 s. Mid-way through the episode some of the goats started jumping over the saturated grid and local workers were forced to corral the goats through it. Thus, the amount of goat

Table 3
Particle size statistics for six sediment samples collected from two saturated grids. Sediment sample masses were 32.450 g (buffalo grid east), 35.020 g (buffalo grid west), 32.339 g (buffalo grid center), 31.917 g (goat grid east), 31.693 g (goat grid west), and 34.876 g (goat grid center). µm = geometric method of moment. Φ = logarithmic method of moment.

	Goat grid (East section)	Goat grid (West section)	Goat grid (Center section)	Buffalo grid (East section)	Buffalo grid (West section)	Buffalo grid (Center section)
Textural sorting	Sandy mud	Sandy mud	Muddy sand	Sandy mud	Sandy mud	Muddy sand
Sediment sorting	Very poorly sorted	Very poorly sorted	Very poorly sorted	Very poorly sorted	Very poorly sorted	Very poorly sorted
Sorting (µm)	5.970	4.169	9.101	4.474	4.823	10.27
Sorting (Φ)	2.578	2.060	3.126	2.161	2.270	3.275
Mean (description)	Coarse silt	Medium silt	Very fine sand	Medium silt	Medium silt	Very fine sand
Mean (µm)	24.86	11.81	55.70	14.37	12.48	58.76
Mean (Φ)	5.330	6.404	3.959	6.121	6.324	3.817
Skewness (description)	Symmetrical	Symmetrical	Fine skewed	Symmetrical	Symmetrical	Fine skewed
Skewness (µm)	−0.152	−0.079	−0.333	0.028	0.242	−0.365
Skewness (Φ)	0.152	0.079	0.370	−0.028	−0.242	0.433
Kurtosis (description)	Platykurtic	Platykurtic	Platykurtic	Platykurtic	Mesokurtic	Platykurtic
Kurtosis (µm)	2.104	2.250	1.848	2.169	2.478	1.773
Kurtosis (Φ)	2.104	2.250	1.886	2.169	2.478	1.849
Gravel	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Sand	34.6%	13.4%	52.6%	19.3%	16.0%	55.0%
Mud	65.4%	86.6%	47.4%	80.7%	84.0%	45.0%
V coarse gravel	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Coarse gravel	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Medium gravel	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Fine gravel	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
V fine gravel	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
V coarse sand	0.0%	0.0%	6.7%	0.0%	0.0%	8.8%
Coarse sand	2.4%	0.0%	16.3%	0.0%	0.5%	19.6%
Medium sand	8.3%	0.3%	16.8%	1.2%	3.9%	15.5%
Fine sand	10.8%	3.7%	6.2%	7.7%	4.3%	5.0%
V fine sand	13.0%	9.4%	6.6%	10.4%	7.3%	6.0%
V coarse silt	13.6%	15.0%	9.1%	13.7%	12.5%	7.7%
Coarse silt	11.7%	15.8%	8.4%	13.9%	14.4%	7.3%
Medium silt	10.9%	15.9%	8.4%	15.4%	15.6%	7.7%
Fine silt	10.7%	15.5%	8.1%	15.7%	15.9%	7.9%
V fine silt	9.5%	13.0%	6.8%	12.8%	13.7%	7.1%
Clay	9.0%	11.5%	6.5%	9.1%	11.9%	7.4%

Table 4
Bulk densities, volumetric water contents (θ), and percentage water contents (u) of sediment samples from the two saturated grids.

	Buffalo grid (East section)		Buffalo grid (West section)		Buffalo grid (Center section)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Wet bulk density g/cm^3	11.27	0.18	12.03	0.14	11.15	1.08
Dry bulk density (40C) g/cm^3	10.85	0.14	11.70	0.16	10.81	1.08
Dry bulk density (105C) g/cm^3	10.82	0.13	11.67	0.16	10.78	1.08
θ (40 °C)	0.42	0.42	0.33	0.02	0.34	0.01
θ (105 °C)	0.45	0.04	0.36	0.02	0.37	0.01
u (40 °C) %	3.75	0.31	2.75	0.16	3.06	0.31
u (105 °C) %	4.02	0.32	2.98	0.17	3.30	0.33
	Goat grid (East section)		Goat grid (West section)		Goat grid (Center section)	
Wet bulk density g/cm^3	11.00	1.10	10.94	1.08	12.01	0.62
Dry bulk density (40C) g/cm^3	10.67	1.08	10.59	1.08	11.65	0.57
Dry bulk density (105C) g/cm^3	10.64	1.08	10.56	1.08	11.63	0.57
θ (40 °C)	0.34	0.03	0.35	0.01	0.36	0.05
θ (105 °C)	0.37	0.03	0.38	0.01	0.38	0.05
u (40 °C) %	3.07	0.19	3.22	0.30	2.95	0.24
u (105 °C) %	3.33	0.19	3.47	0.32	3.19	0.25

trampling the saturated grid received varied with each pass. However, as the results below indicate, this does not seem to have significantly influenced any patterning.

2.6. Post-trampling recording

Data (x, y, z, maximum inclination) from the experimental flakes in the dry grids were recorded immediately, after which the flakes were collected and placed in numbered zip-lock bags. The saturated grids were allowed to dry and harden over the course of three days. To discourage further disturbance by humans or animals during the drying period, the grids were encircled with *Acacia* branches. Once the encasing sediment was dry, the artifacts were carefully excavated, but left *in situ* so location and arrangement data could be recorded before their removal.

Fig. 3. Water buffalo trampling the saturated grid.

Four experimental flakes were lost during the course of the trampling experiment: one from the buffalo dry grid, two from the buffalo saturated grid, and one from the goat saturated grid. We suspect the flake lost from the dry grid was kicked some distance from the experimental area, while the flakes lost from the saturated grids may have been "caked" with mud onto the bottom of animal hooves and carried away.

3. Results

All pre- and post-trampling data are available for download in the online *Journal of Archaeological Science* Supplementary materials. Statistical tests of significance below are evaluated with an alpha-level of 0.05.

3.1. Horizontal displacement

We hypothesized that horizontal artifact displacement would be greater in the dry grids, where the artifacts were not adhering to saturated mud. We also expected the buffalo trampled grids to yield higher horizontal displacements than the goat trampled grids. This is because the more powerful buffalo can kick the artifacts further in the dry grids, while the larger surface area of the buffalo hoof might provide a better chance for an artifact to stick to it and be carried horizontally in the saturated grids.

Despite these expectations, two-sample *t*-tests show no statistically significant difference regarding horizontal artifact displacement among any of the grid variations (Fig. 4). Overall the buffalo trampled grids exhibited larger and more frequent outliers (horizontal displacement greater than 40 cm) than goat trampled grids (compare column 1 and 2 vs. 3 and 4, Fig. 5). Also, the dry grids possessed outliers of greater value than the saturated grids (compare column 1 and 3 vs. 2 and 4, Fig. 5). Nevertheless, each grid exhibited a horizontal displacement mean value between 10 and 20 cm, and there is enough overlap between each grid population that we suggest neither moisture content nor animal type significantly influences horizontal displacement, given our particular substrate.

As mentioned previously, both the buffalo and goats trampled their respective grids in two opposing directions. This method probably influenced the results of horizontal displacement since each displaced artifact had a chance to be kicked back to or near its original position. For horizontal displacement, our experiment best serves as an analogy to animals moving about in multiple directions (i.e. on a riverbank or around a watering hole), rather than a one-way migration in a single direction.

Comparing our data to previous experiments, only Nielsen (1991, Table 1) provides a mean and range of horizontal displacement for lithic artifacts. In one trampling grid (TR-II) he reports a mean horizontal displacement of 23.9 cm and a range of 0.0–126.0 cm. In another trampling grid (TR-III) he reports a mean of 19.2 cm and a range of 0.0–122.0 cm. All of our trampling grid variations exhibited lower means and ranges (Table 5). Given that there is no statistical relationship between horizontal displacement, saturation, or animal, we attribute the differences between Nielsen's (1991) study and our own to our shorter trampling time.

We found no relationship between artifact size and horizontal displacement in any grid variation. Linear correlations are virtually nonexistent (dry buffalo grid, $r = -0.0245$; saturated buffalo grid, $r = -0.2128$; dry goat grid, $r = -0.2133$; saturated goat grid, $r = 0.2074$) suggesting that artifact size plays little role in horizontal displacement given our materials and substrate. This lack of correlation between artifact size and horizontal displacement concurs with a number of other studies (Nielsen, 1991; Pintar, 1987, as cited by Nielsen, 1991: 490; Villa and Courtin, 1983).

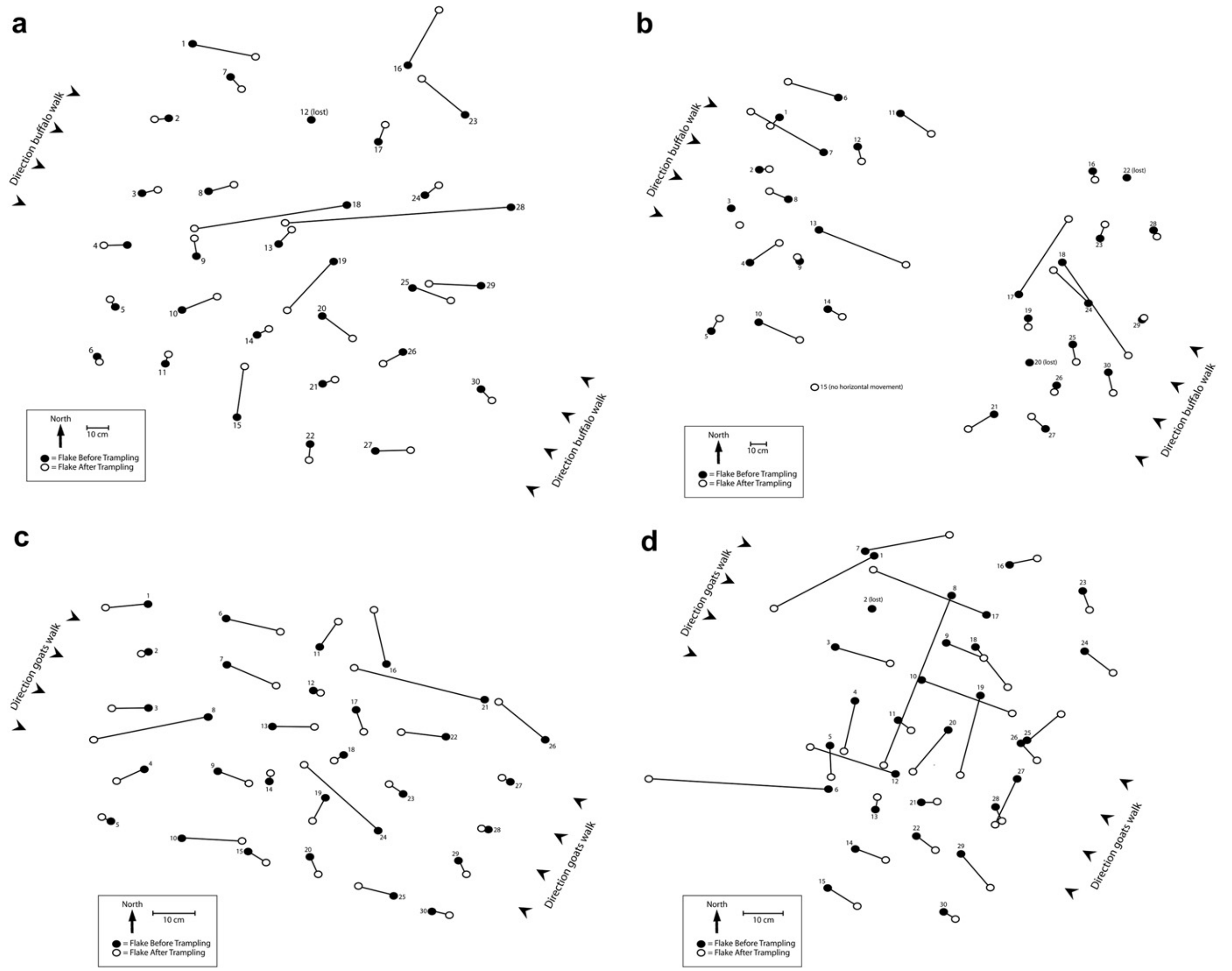

Fig. 4. Plots of horizontal artifact displacement from each grid before and after trampling: water buffalo dry (a); water buffalo saturated (b); goat dry (c); and goat saturated (d).

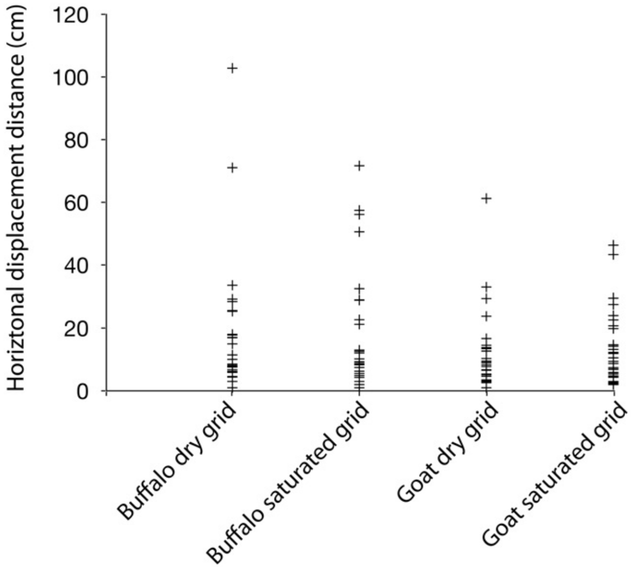

Fig. 5. Distribution of horizontal artifact displacement from each experimental grid after trampling.

3.2. Vertical displacement

We expected the artifacts in the saturated grids to exhibit more vertical displacement than those in the dry grids, because saturated sediments are weaker and more prone to deformation under applied stress. We also expected the buffalo trampled artifacts to exhibit greater vertical displacement than those trampled by the goats, since the buffalo are much heavier and thus would push the artifacts deeper into the ground.[1]

Fig. 6a–d shows vertical artifact displacement without consideration of the original ground surface's natural vertical undulations. Immediately striking is the tendency of the artifacts to move upward in the dry grids (Fig. 6a, c). We attribute this to two possible factors. First, the artifacts may be being kicked onto higher elevations within the grid. Alternatively, displaced substrate kicked loose by the trampling animals may be elevating most of the dry grid surface as a whole, since loose and crumbled substrate takes up more volume than compacted substrate. While the saturated grids

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[1] Wild water buffalo weight ranges from 700 to 1200 kg. Domesticated water buffalo weight ranges from 250 to 550 kg. Goat weight ranges from 25 to 95 kg. See Mason 1974; Nowak 1999.

Table 5
The mean and range of each grid's horizontal artifact displacement.

Grid	Horizontal Displacement Mean (cm)	Range (cm)
Dry buffalo grid	17.9	101.8
Saturated buffalo grid	17.8	71.7
Dry goat grid	11.5	60.3
Saturated goat grid	13.5	44.4

show an overwhelming pattern of downward vertical displacement, the tendency for upward movement was not limited entirely to the dry grids, as six of the artifacts in the two saturated grids also show upward vertical displacement (Fig. 6b, d). We suspect that these upward-moving artifacts were "squeezed" upward by an animal hoof landing just adjacent to the artifact. As the hoof replaced substrate volume in the ground, displaced substrate was forced horizontally, in turn pushing upwards adjacent substrate and any artifacts.

Since the artifacts were for the most part distributed evenly across their respective grids, their original elevations provide a rough record of the ground surface's natural vertical undulations. Fig. 7 again shows artifact displacement, but this time in relation to the maximum range of the ground's vertical variation (depicted in gray). Only the artifacts in the saturated grids penetrated any depth below their experimental "stratigraphic" surface (Fig. 7b, d).

There is a statistically significant difference between the vertical artifact displacement mean values of dry and saturated grids. Two-sample *t*-tests indicate that the buffalo trampled dry grid exhibited significantly less displacement than its saturated counterpart ($p < 0.0001$), while the goat trampled dry grid also exhibited significantly less than its saturated counterpart ($p < 0.0001$). Results from inter-species comparisons match less well with expectations. Two-sample *t*-tests indicate that there was no statistically significant difference between the buffalo and goat trampled dry grids ($p = 0.5311$), nor was there any difference between the buffalo and goat trampled saturated grids ($p = 0.6596$).

Our trampling experiment in saturated sediments led to greater vertical displacement than has been previously documented. In compact substrates, Villa and Courtin (1983) recorded a maximum vertical displacement of 8.0 cm, Gifford-Gonzalez et al. (1985) recorded 3.0 cm, and Nielsen (1991) recorded 1.5 cm (all used human trampling). Our buffalo trampled saturated grid showed a *mean* vertical displacement of 6.5 cm and maximum vertical displacement of 21.0 cm. Our goat trampled saturated grid showed a mean vertical displacement of 6.0 cm and a maximum vertical displacement of 16.0 cm.

Stockton (1973) did not report vertical displacement, but instead the maximum vertical distance of artifact separation, which in loose sandy soils he found to be 16 cm. Our buffalo trampled saturated grid exhibited a maximum distance of artifact separation

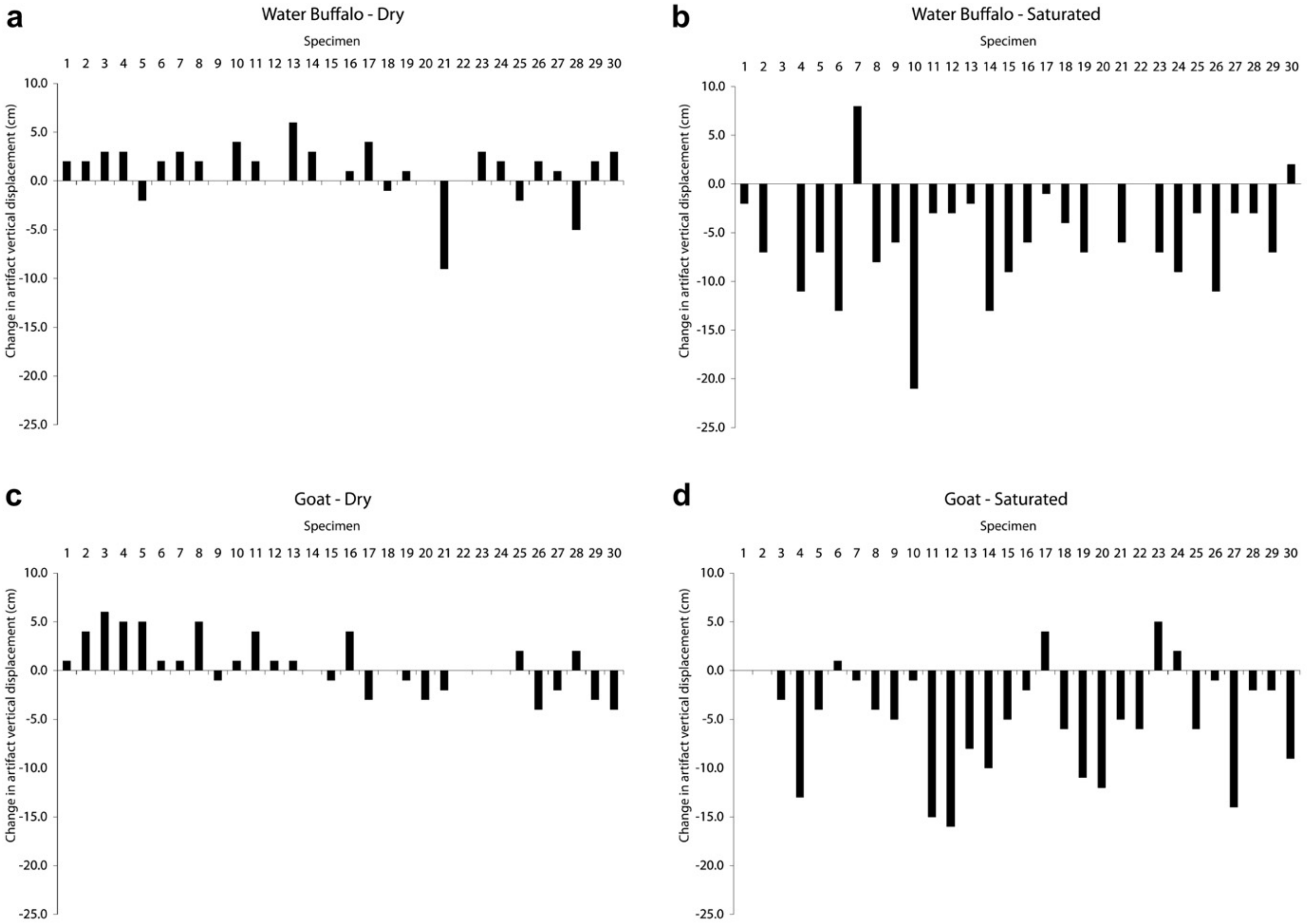

Fig. 6. Plots of absolute vertical artifact displacement from each grid before and after trampling: water buffalo dry (a); water buffalo saturated (b); goat dry (c); and goat saturated (d).

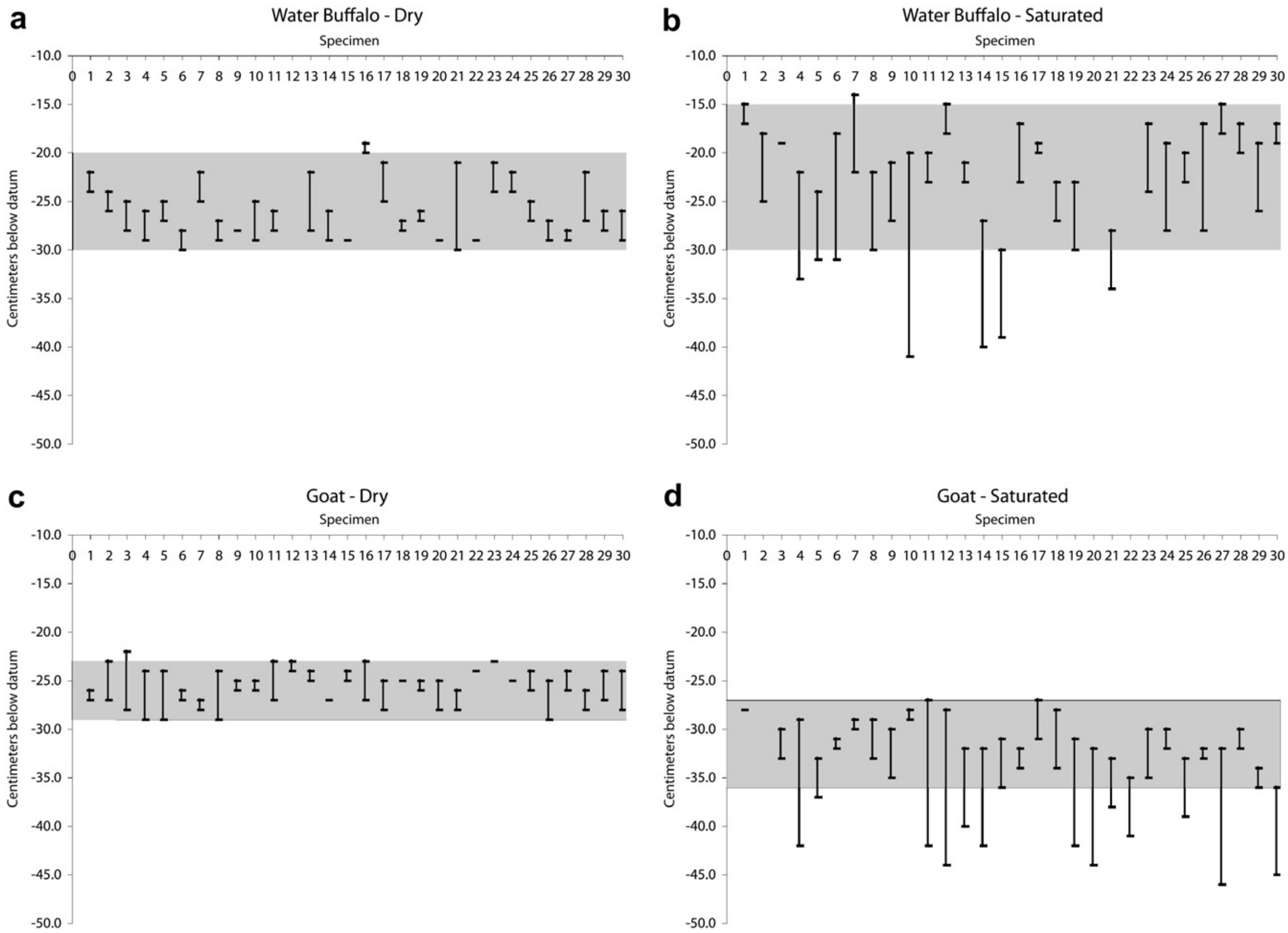

Fig. 7. Plots of vertical artifact displacement in relation to the natural ground's original vertical undulations from each grid before and after trampling: water buffalo dry (a); water buffalo saturated (b); goat dry (c); and goat saturated (d).

of 27 cm, while our goat trampled saturated grid exhibited a distance of 19 cm.

Artifact size appears to have little influence on vertical displacement. Other than a weak positive correlation in the goat trampled dry grid ($r = 0.4506$), there appears to be no relationship between artifact size and vertical displacement (dry buffalo grid, $r = 0.1127$; saturated buffalo grid, $r = 0.0224$; saturated goat grid, $r = 0.0224$). Interestingly, while a number of experiments have reported correlations between artifact size and vertical displacement (Muckle, 1985 as cited by Nielsen, 1991: 488; Pintar, 1987 as cited by Nielsen, 1991: 488), others do not (Gifford-Gonzalez et al., 1985; Nielsen, 1991; Villa and Courtin, 1983). Ours showed agreement with the latter, with the differences most probably due to different mechanisms of displacement and substrate types.

3.3. *Artifact breakage*

During knapping experiments, M.I.E. noted that the local limestone often broke along natural cleavages during core reduction, but is otherwise is a tough material that produces durable edges. Indeed, there was very little breakage or edge damage on any of the trampled flakes. Only twelve of the 120 flakes (10%) showed any sort of macroscopic damage. Other than one flake which was snapped in half along its longitudinal axis (Fig. 8a) and another whose distal end was broken off (Fig. 8b), the rest of the damaged flakes only showed the most minimal edge modification (Fig. 8c, d). The edge damage could not be mistaken for systematic retouch, as it involved only single small chips. Of the twelve damaged flakes,

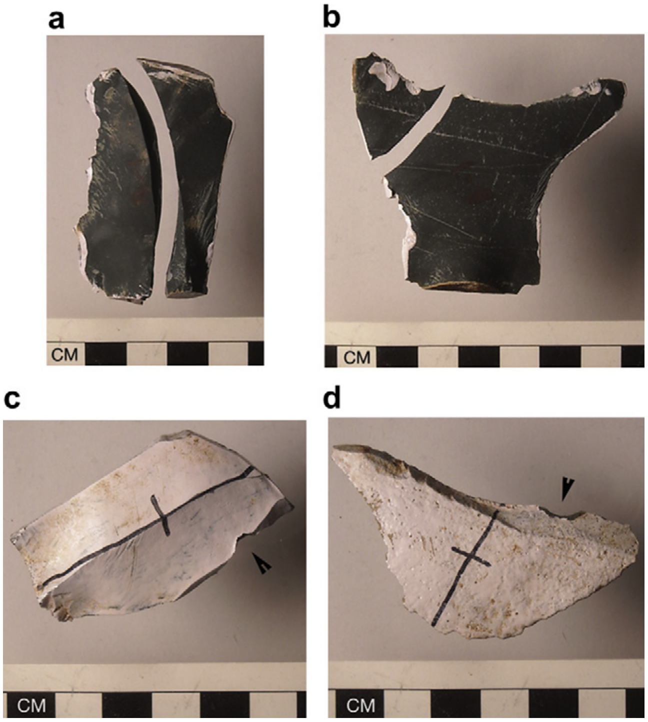

Fig. 8. Examples of artifact breakage during the experiment. One artifact was split down its axis of percussion (a), while another had its distal end broken off (b). However, all other damaged artifacts only exhibited single small chip removals (c, d).

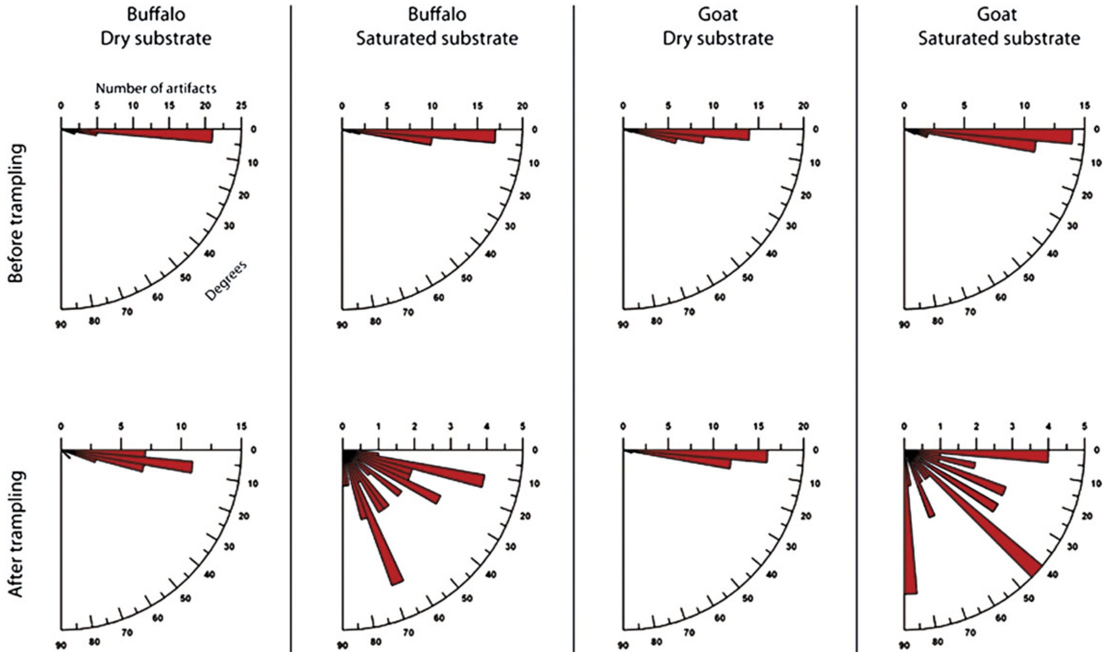

Fig. 9. Rose diagrams of artifact inclination recorded from each grid before and after trampling.

four came from the buffalo dry grid (including the two snapped flakes), two came from the buffalo saturated grid, and six came from the goat saturated grid.

Previous experiments (e.g. Gifford-Gonzalez et al., 1985; Lopinot and Ray, 2007) have shown that substantial artifact damage can occur during trampling, even resulting in identifiable tool "types" (McBrearty et al., 1998). Our experiments differ from these results, as none of our trampled grids showed a substantial number of damaged flakes. We propose four potential reasons for this. First, as shown in Table 1, our trampling episodes were shorter in duration than other experiments that trampled stone flakes. Artifacts simply did not experience enough trampling to accumulate large amounts of damage. Secondly, artifacts in the saturated grids artifacts were not subject to the same amount of force as they would be in other circumstances. Third, there was a lack of gravel and pebbles in our substrate. Finally, the limestone was tough enough to withstand the trampling.

3.4. Artifact inclination

The artifact inclination disparity between dry and saturated substrates was pronounced (Fig. 9), which we attribute to artifacts in the wet substrate having more freedom to rotate, both under direct pressure and when influenced by nearby sediment deformation or displacement. Two-sample *t*-tests show artifacts trampled in dry substrates possessed statistically lower inclination values than those trampled in saturated substrates, regardless of trampling agent (buffalo dry versus saturated, $p < 0.0001$; goat dry versus saturated, $p < 0.0001$). Additionally, and perhaps more importantly for diagnostic purposes, *F*-tests show that artifact inclination standard deviation was significantly larger in the saturated grids than in the dry (buffalo dry standard deviation = 7.7889, buffalo saturated standard deviation = 25.7862, $p < 0.0001$; goat dry standard deviation = 4.5524, goat saturated deviation = 29.5928, $p < 0.0001$).

Considering only the dry grids, two-sample *t*-tests show that the buffalo trampled artifacts exhibited a statistically larger mean inclination than the goats trampled artifacts ($p = 0.0180$), but an *F*-test shows their standard deviations were statistically similar ($p = 0.8673$). We attribute the larger inclination value to the greater weight and pressure[2] the buffalo exerted when trampling the artifacts into dry sediment. In saturated grids there was no statistical difference between the buffalo or goats in mean inclination value (two-sample *t*-test, $p = 0.6934$) or inclination standard deviation (*F*-test, $p = 0.4768$).

4. Summary and discussion

Short-period animal trampling caused equal amounts of horizontal displacement in dry and saturated substrates. Vertical displacement was significantly greater in the saturated substrates. Overall, vertical displacement, and maximum distance of artifact separation in our saturated grids was greater than any previously reported trampling experiment. Artifact breaks and damage to lateral edges was minimal, doubtless a product of the short-period design of this experiment. Artifact inclination patterning appears to distinguish trampling in saturated as opposed to dry substrates in the modern Jurreru Valley. Given the large vertical displacements associated with saturated substrates, a marker of disturbance such as inclination would be welcome. Of course, context is key – other types of sites may produce artifacts with steep and variable inclinations (e.g. caves, McPherron, 2005), while other

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[2] To support this statement (albeit very roughly) it is possible to calculate the pressure that water buffalo and goats exert on the ground while standing. Pressure is defined as force per unit area, where force F is understood to be acting perpendicular to the surface area A:Pressure $(P) = F/A$Taking the middle weight of domesticated water buffalo to be 400 kg (Nowak, 1999), we know that the standing force of a buffalo to be 3920 N (400 kg × 9.8 m/s^2). If we estimate the area of one hoof (unsplayed) to be 108 cm^2 (Zhang et al., 2008: 80, Fig. 1), four hooves would encompass an area of 432 cm^2. Thus, water buffalo standing pressure would equal9.07 N/cm^2 = 3920 N/432 cm^2.Goats' middle weight is 60 kg (Nowak, 1999), and thus standing force is 588 N. A goat hoof measured by M.I.E. from the SMU faunal reference collection had a rough (unsplayed) area of 19.6 cm^2. Four goat hooves would encompass an area of 78.4 cm^2. Thus goat standing pressure would equal7.5 N/cm^2 = 588 N/78.4 cm^2.

processes may ameliorate these steep inclinations (e.g. sediment consolidation, e.g. Andrews, 2006). But for archaeological sites near water-bodies with similar substrates, the results presented here suggest that artifact inclination patterning is a promising avenue for recognizing trampling disturbance since inclination can preserve archaeologically. Surely, artifact inclination should be recorded in future field work undertaken at such sites.

Though archaeologists working in India are certainly aware of the influence of natural processes in forming spatial patterns (e.g., Paddayya, 1987; Petraglia, 1995), little attention has been paid to disturbance by trampling in either an experimental or archaeological context. One site context that raises the possibility for trampling is the Pleistocene site of Attirampakkam. Pappu and Akhilesh (2006: 163) note:

> A study of inclination patterns for all *in situ* tools points to a high percentage being horizontally embedded ($n = 62$ in Layer 6 and $n = 89$ in Layer 5) or at angles smaller than 50° to the horizontal. However, when one considers the assemblages in all layers, a high percentage of tools were inclined at angles greater than 50° or were vertical. For handaxes and cleavers, almost equal percentages were flat ($n = 27$) and inclined to vertical or varied angles ($n = 21$). A total of 9 tools were fully vertical and seven inclined at angles greater than 50°; of these, four are cleavers and the rest handaxes. Two tools were inclined along their breadth, with the rest being embedded along the pointed apex/butt. The reasons for this are as yet unclear…

Given that Pappu et al.'s (2003) studies indicate a flood-basin environment for the site, we suggest that artifact inclination patterning might be in part a result of animal trampling in addition to other processes such as argilliturbation, or the shrinking and swelling of sediments due to wetting and drying. That animal footprints and remains of *Bubalus* (or *Bos*), *Equus*, and *Boselaphus* (or *Capra*) are present makes this possibility all the stronger. We acknowledge that the handaxes and cleavers found at Attirampakkam are much larger lithic tool types than the ones experimentally tested here. However, the footprints found there are fairly large as well, measuring 15–20 cm in diameter (ibid. 596), suggesting that the animals associated with them could have contributed to artifact re-orientation at the site.

Given that during the Lower and most of the Middle Pleistocene hominins stayed close to water sources (Bar-Yosef, 2006: 488; Dominguez-Rodrigo and Alaca, 2009: 7), we cannot help but wonder how prevalent saturated substrate trampling might be, and how it has affected the context, and resulting interpretation, of Paleolithic sites throughout the Old World.

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Appendix. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jas.2010.06.024.

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