DEFINING SUITABILITY IN MIXED AGROPASTORAL SOCIETIES: A CASE STUDY FROM BACTRIA IN NORTHERN AFGHANISTAN

This paper explores the concept of suitability within applications of Ideal Distribution Models (IDMs). Specifically, we investigate the effectiveness of single measures of suitability in contexts where diverse local populations practiced a range of subsistence strategies with different environmental requirements and sociocultural consequences. To do so, we draw on legacy survey data from northern Afghanistan, within the historic region of Bactria. This region of Central Asia has a rich history of nomadic pastoralism as well as dense urban settlement, with these two lifeways often occurring concurrently with complex social and economic interdependencies developing between pastoral and agricultural societies. Conceptually, we predict that such diversity should be difficult to model by conventional IDMs, as what may be defined as a low ranked habitat by one definition of suitability may be highly ranked in another. On the other hand, identifying strong deviations from IDMs may in fact indicate shifts in subsistence strategies and settlement patterns occurring across various periods of sociopolitical and cultural change. Based on our analysis, we conclude that single measures of suitability do not sufficiently model settlement patterns as predicted by IDMs but do in fact help highlight long-term processes of ecological engineering and inheritance.

Keywords: Suitability, Ideal Distribution Models, Bactria, Afghanistan, Pastoralism

Word count: 6283

Funding details: None

Daniel Plekhov Joukowsky Institute for Archaeology and the Ancient World, Brown University, 60 George St. Providence, RI 02912, USA (daniel_plekhov@brown.edu, corresponding author) <https://orcid.org/0000-0002-4594-7180>

Daniel Plekhov is a graduate student at the Joukowsky Institute for Archaeology and the Ancient World at Brown University. He studies agricultural infrastructure and long-term processes of landscape modification and ecological inheritance.

Evan I. Levine Joukowsky Institute for Archaeology and the Ancient World, Brown University, 60 George St. Providence, RI 02912, USA (evan_levine@brown.edu) <https://orcid.org/0000-0002-2379-9965>

Evan I. Levine is a graduate student at the Joukowsky Institute for Archaeology and the Ancient World at Brown University. He is a specialist in regional survey and focuses on rural religion.

1 Introduction

2 Suitability is a central parameter of Ideal Distribution Models (IDMs), within which it is
3 used to predict where individuals should choose to live based on the quality of habitats and the
4 number of individuals already in those habitats (Fretwell and Lucas 1969). The suitability of
5 these habitats is relative, being based both on environmental factors such as resource availability
6 as well as on positive and negative density dependencies arising from population increases.
7 These density dependencies can lead to increasing suitability (through economies of scale or
8 collective labor; also referred to as Allee effects [Kramer et al. 2009]), or to decreasing
9 suitability (through resource stress or social conflict). Based on assumed perfect knowledge of a
10 region and its suitabilities, individuals will settle and move between habitats to maximize their
11 survival and reproductive fitness, thus achieving a balanced settlement distribution (the ideal free
12 distribution). From this model arises other predictions, such as that the most suitable habitats will
13 be occupied first, will always have the highest population density, and will remain occupied
14 longest (Winterhalder et al. 2010: 473).

15 IDMs carry with them certain assumptions that must be acknowledged when applied to
16 archaeological contexts. Some of these assumptions are that all individuals in a population have
17 similar abilities, that suitability can be measured according to a scale common to all habitats
18 being considered, and that there are no impediments to movement to or from a habitat
19 (Winterhalder et al. 2010: 471).

20 A potentially more problematic and fundamental assumption is that all individuals in a
21 population have the same requirements and that, even with perfect knowledge of all habitats, will
22 agree on which habitat is the most suitable. Most cases to which IDMs are applied assume
23 homogeneity of subsistence practices for the populations being modeled. For most studies this is
24 a fair assumption, where despite factors such as seasonality, environmental degradation, or
25 despotic behavior, changes in subsistence practices are reasonably assumed to be constant across
26 the modeled populations (Kennett et al. 2006; McClure et al. 2009; Pufer et al. 2017). With these
27 assumptions of subsistence constancy, IDM studies have been successfully applied for hunter-
28 gatherer, pastoralist, and agricultural societies (Moritz et al. 2013; Tremayne and Winterhalder
29 2017; Yaworsky and Coddington 2018), though rarely including more than one of these groups.
30 Studies by Lambert and Welker (2017, 2019) do apply IFD to investigate incidences of traumatic
31 injury among agriculturalists and foragers, though the emphasis is less on settlement than on the
32 health consequences of different subsistence strategies. We are unaware, therefore, of any studies
33 thus far that have applied IDM models to settlement patterns where populations of different
34 subsistence strategies are prominently represented. Given the often-pronounced differences in
35 mobility, population density, and environmental requirements between hunter-gatherer, pastoral,
36 and agricultural subsistence strategies (Barnard and Wendrich 2008; Cribb 1991), it is worth
37 considering whether applications of IDMs to case studies that include these different groups can
38 effectively model settlement patterns using a single measure of suitability. In other words, if the
39 settlement pattern at any given time reflects the needs and preferences of both agricultural and
40 pastoral strategies, can one measure of suitability model these distributions under the
41 assumptions of the IDM?

42 To explore this issue further, we investigate the settlement history of Bactria, a variably
43 defined region that at one point encompassed parts of several modern countries in Central Asia
44 (Fig. 1). This region is ideal for this study because of its seemingly contradictory classification
45 as both the “land of a thousand cities” (Justin 41.1.8) as well as one famous for its highly mobile
46 nomadic peoples. These contradictions are well attested by archaeological and historical sources

that show the widespread practice of both subsistence strategies within the region (Kidd and Stark 2019; Rouse and Cerasetti 2018; Stride et al. 2009). We examine how the settlement pattern of the region reflects these different strategies, with shifts in settlement through time possibly reflecting changes in the relative investments of local communities in one strategy or the other. We draw on data from northern Afghanistan compiled from the revised *Archaeological Gazetteer of Afghanistan* (Ball 2019), which synthesizes data from archaeological excavations, surveys, military reconnaissance, and local reports to document archaeological sites in the region from the Paleolithic to the 16th century Timurid Empire.

All included sites we take each site location to represent a habitat, being sufficiently large in extent for settlement and with a suitability different than that of other habitats (Winterhalder et al. 2010: 471). By calculating suitability for each site location, we investigate settlement pattern change through time and compare these patterns to those predicted by IDMs. To better define the parameters of our study, we test three predictions of these models:

1. The first habitats settled will be the most suitable.
2. The most suitable habitats will be occupied longest.
3. The average suitability of a settlement pattern should decrease as sites increase in number.

Together, testing these predictions according to single measures of suitability allows us to evaluate how effectively these metrics model settlement distribution and change through time. To be clear, it is not the fundamental predictions of IDMs themselves that we are testing here, but rather the assumptions about suitability that determine their application. As Winterhalder (2002: 210) writes, testing a model's predictions allows one to test its assumptions as well.

Thus, to test the predictions outlined above, we employ two simplistic measures of suitability to model the distribution of settlement according to agricultural and pastoral subsistence strategies. Generating these models allows us to investigate if settlement patterns deviate from the predictions of IDMs when employing these assumptions about homogenous subsistence economies. We employ mean annual Normalized Difference Vegetation Index (NDVI) values, which measure the relative health of vegetation, to calculate the suitability model for the case of a subsistence strategy that is prevalingly directed towards agriculture. Sites with the highest NDVI values are presumed to be the most suitable for agriculture, based on the assumption that healthy vegetation corresponds to agricultural productivity. For the suitability model based on a pastoralist strategy, we calculate the standard deviation of elevation values within 10 km buffers of each site. Sites with the highest elevation standard deviations (ESD) are presumed to be the most suitable for pastoralism, with the assumption that access to upland and lowland areas is ideal for pastoral needs. Further information and justification for these proxies is provided below.

Yet both agricultural and pastoralist strategies were practiced concurrently by different segments of the regional population (Stride et al. 2009). The resulting settlement pattern of Bactria may then have reflected the different requirements of these subsistence strategies, either through preference to locations that balance suitability of both practices (e.g. relatively high NDVI and ESD) or through two fairly independent settlement patterns that each maximize suitability according to one subsistence strategy or the other. Evidence of these kinds of settlement patterns in the data will demonstrate the limitations of employing measures of

suitability that assume all individuals in a population have the same requirements and perceptions of suitability.

The Steppe and the Sown

The relationship between pastoral and agricultural subsistence economies has often been characterized in stark and opposing terms, expressed best as the distinction between the steppe and the sown (Peake and Fleure 1928). This characterization views agricultural and pastoral societies as conceptually and spatially distinct, with each internally homogenous in their subsistence practices and foodways and each occupying a particular ecological niche (Brite et al. 2017). While distinctions do certainly exist between these different strategies, in practice they have far more complex and entangled relationships and are often not easily distinguished (Chang 2018; Khazanov 1994; Spengler et al. 2013; Stride et al. 2009). Pastoral nomads have been known to organize irrigated cultivation systems even while maintaining high investments in pastoralism and mobile ways of life, while agriculturalists frequently raise animals and engage in short-range transhumance (Honeychurch and Amartuvshin 2007; Spengler et al. 2017; Taylor et al. 2018). Beyond these overlaps, both agricultural and pastoralist communities often benefit from and rely on each other for services and resources arising from exploitation of these different ecological niches (Brite et al. 2017; Honeychurch and Makarewicz 2016; Rouse and Cerasetti 2018; Wu et al. 2015). In a more pronounced case, such as which frequently arose in Bactria, expansive nomadic states emerged that incorporated agricultural societies, which continued to thrive within these nomadic states (Alizadeh 2010; Honeychurch 2014; Miller et al. 2019; Soucek 2000: 41-45). The emergence and persistence of settlements within these distinctly nomadic contexts, in both steppe and lowland areas, shows the dynamic nature of these subsistence strategies and social interactions (Honeychurch and Amartuvshin 2007).

Since our study investigates agricultural and pastoral practices, we must contend with the well-known problem of nomadic sites having lower archaeological visibility than more sedentary sites (Cribb 1991: 65–83; Honeychurch and Makarewicz 2016: 349-350). Nomadic sites often have less standing architecture and material culture on the surface, making them both difficult to locate and date. The high mobility of nomadic groups also results in more ephemeral, and more numerous, sites that may be only seasonally occupied or abandoned for many years (Frachetti and Maksudov 2014; Ur and Hammer 2009). Any archaeological gazetteer is thus likely to misrepresent or simply exclude a large portion of sites associated with pastoral activity, thereby potentially skewing interpretations towards more sedentary lifestyles.

Yet while nomads are etymologically and conceptually linked to pastoralism, the term has come to more broadly apply to any form of residentially mobile existence regardless of motivation or form of social organization (Wendrich and Barnard 2008: 3-5). In this broader sense, there are a diversity of nomadic lifestyles by which either entire groups move together or only some portion of the group moves, with the distances and durations of movement varying based on subsistence strategies, seasonality, or local resource availability. All mobile lifestyles require some stationary periods, either for production of goods, for social events, or simply for sleep (González-Ruibal and de Torres 2018; Weeks et al. 2018), and not all segments of a nomadic population are necessarily mobile year-round (Wendrich and Barnard 2008: 10-11). We therefore avoid categorizing sites as agricultural or pastoral, lacking the information to make such a determination and recognizing that such classifications are likely misleading at best.

As the brief historical review below will discuss, local groups practiced both agricultural and pastoral subsistence strategies throughout the period of time covered by this study. How

distinct these groups were from each other at any given time is less important than the recognition that both ways of life continued to define the overall subsistence economy of the region. We are therefore careful to avoid reinstating a distinction between the steppe and the sown. Recognizing that all settlements would have been places of interaction and exchange between communities practicing both subsistence strategies, our analysis of site distributions is not meant to draw boundaries between these groups nor to associate some sites with one or the other. Rather, we investigate the overall distributions of sites and their relations to variables we consider relevant for agricultural or pastoral practices. By evaluating the relationship between settlements and these variables, we test the application of IDMs to this kind of dataset.

Regional Context

Bactria's history of ever-shifting political borders makes defining it geographically difficult. Though our dataset comes definitively from within the limits of the modern state of Afghanistan, the overall extent of Bactria at any given time may not have included all of these sites. From the *Archaeological Gazetteer of Afghanistan* (Ball 2019) we have selected a subset of sites from provinces bordering the Amu Darya river, which defines Afghanistan's northern border, and those slightly to the south (Hirat, Badghis, Faryab, Jawzjan, Sari Pul, Balkh, Samangan, Bamyan, Parwan, Baghlan, Kunduz, Takhar, and Badakhshan). Furthermore, much of Bactria can be said to extend to areas north of the Amu Darya river as well, stretching into modern day Turkmenistan, Uzbekistan, and Tajikistan (Leriche 2009; Stride 2009: 114-115). We exclude these areas from our study due to their absence from the *Archaeological Gazetteer of Afghanistan*. Though comparable gazetteers and databases exist for the area north of the Amu Darya, particularly the Surkhan Darya in southern Uzbekistan (Stride 2004a, Stride 2004b), the typological and chronological schemes differ, thereby potentially introducing further inconsistency into what is already an amalgam of different datasets. Our study thus focuses on the southern floodplains of the Amu Darya, the drainages from the Hindu Kush that create the oases around Balkh and Kunduz, and the foothills and valleys of the Hindu Kush itself.

This topographically varied landscape provides a broad variety of ecological zones. Steppe grasslands are bordered by vast arid deserts, interspersed with highly fertile but constrained river deltas and lowlands. This divergent combination of hot and cold, wet and dry, high and lowlands demonstrates clearly the variety of ecological niches that local populations had access to and the potential of the landscape for both pastoralism and agriculture. While variations in climate are expected for the timespan we are studying, climatic records indicate that rainfall was generally at or below the 200 mm per year limit necessary for dry agriculture, as it is today (Fouache et al. 2012: 3417; Wordsworth 2018: 184). Archaeological study of botanical and faunal remains indicates that wheat, barley, and pulses were the predominant domesticated crops while sheep/goat, cattle, and horses were the focus of most pastoral activity (Rouse and Cerasetti 2018; Spengler and Willcox 2013; Taylor et al. 2018).

The dataset we draw on from the revised *Archaeological Gazetteer of Afghanistan* (Ball 2019) covers the period from the Middle Paleolithic to the Turco-Mongolian Timurid Dynasty, some 50,000 years of history. Due to the objectives of our study, however, we exclude phases with Paleolithic and Neolithic materials. This is due to the fact that hunting and gathering was the only subsistence strategy practiced during the Paleolithic, while during the Neolithic agriculture and pastoralism were still emergent and practiced concurrently with exploitation of wild resources (Dani and Masson 1992: 20; Derevyanko and Zun-E 1992; Sarianidi 1992). It is only in the Bronze Age and forward, beginning in the third millennium BCE, that we can

reasonably assume that settlement patterns began to reflect the needs of agricultural or pastoral subsistence strategies, though the adoption of these strategies was highly variable across parts of Bactria (Frachetti and Maksudov 2014; Motuzaite Matuzeviciute et al. 2015; Spengler et al. 2014). Exploitation of wild resources continued then, much as it does today, but would have represented an increasingly smaller proportion of the subsistence economy.

Space does not allow for a thorough review of the history of this region from the Bronze Age to the sixteenth century CE (for which, see Asimov and Bosworth 1998; Ball and Hammond 2019; Cribb and Herrmann 2009; Harmatta et al. 1996; Litvinsky et al. 1996). Our treatment of it here is therefore meant to primarily highlight the role of agricultural and pastoral subsistence strategies through time rather than to discuss the particular sociopolitical changes that occurred over the past 4000 years.

The Bronze Age (4000–1500 BCE) is associated with the so-called Bactria–Margiana Archaeological Complex (BMAC), which provides the first clear archaeological evidence for urbanism in the region (Tosi et al. 1992). Evidence of irrigation from this period also shows the growing investment in agricultural production, which would have required additional water input due to the low rainfall of the region (Miller 2003). Pastoralism is also evident in this period, with rich burial mounds and “surprisingly similar” faunal assemblages attesting to the interconnectedness and networks that connected nomadic groups across much of Central Asia (Frachetti 2012; Kohl 2007; Sarianidi 2005; Spengler 2015).

The Iron Age (1500–521 BCE) was a period of apparent instability and transformation, with evidence of hostile incursions by nomadic groups, the breakdown of inter-regional trade networks, and the reconfiguration of regional settlement patterns (Rouse and Cerasetti 2017; Rouse and Cerasetti 2018; Salvatori 2008). By 520 BCE, Bactria was conquered by the Achaemenid Persian Empire, which expanded and intensified what may have been a pre-existing system of agricultural infrastructure and water management (Francfort and Lecomte 2002; Gardin 1998: 156; Wu et al. 2015). This development continued throughout the Seleucid and Greco-Bactrian periods (Mairs 2014: 27–56). The continued use and maintenance of these irrigation systems, some even to the present day, underscores their importance and necessity in this region (Rouse and Cerasetti 2017; Wordsworth 2018).

By the mid-first century BCE, Bactria was conquered by the nomadic Yuezhi Kushans, who greatly expanded the borders of the Bactrian kingdom (Liu 2001). They themselves were followed by Sasanian Persians, Turks, Mongols, Hephthalite Huns, and successive Islamic empires. These groups followed each other in relatively quick succession, with few retaining control for more than a century or so (Asimov and Bosworth 1998). Many of the states which came to rule Bactria were nomadic, yet surprisingly it was during many of these periods that settlement increased and new cities were established (Leriche 2009: 144–148). Nomadic invasions in the thirteenth century CE, particularly those by Genghis Khan and the Chagatai Khanate, caused widespread destruction and devastation, while rule by the nomadic Timurid Dynasty a century later led to urban growth and resettlement (Soucek 2000: 117–126). With each invasion and sociopolitical reorganization, there is evidence for continuity of agricultural and pastoral practice (Frachetti and Maksudov 2014; Wordsworth 2018). By studying changes in the settlement pattern across these different periods, we evaluate whether they conform to predictions made by IDMs according to single measures of suitability.

Data

Having selected only those sites in the *Archaeological Gazetteer of Afghanistan* (Ball 2019) from the northern provinces of Afghanistan, and excluding those with only Paleolithic or Neolithic phases, we digitized the relevant records and mapped them according to their associated coordinates. In addition to latitude and longitude, each site is also associated with data about its periods of occupation (Table 1), its site type, description of the site, the type of fieldwork responsible for documenting it, and the relevant citations. Though a wide range of site types are classified within the gazetteer, including mounds, settlements, forts, caravanserais as well as those with religious or production functions (e.g. temples, irrigation systems), we chose not to exclude any so as to avoid imposing additional bias and making assumptions about how sites could be used. Indeed, many sites have several of these attributes associated with them. Additionally, because of the range of survey projects synthesized in this gazetteer, with some having taken place as early as the late 19th century and others involving only individual travel accounts, the internal consistency of these data is likely to vary and misidentifications are possible (Ball 1982: Appendix 3). Our final dataset therefore includes 583 unique site locations with many occupied across several periods. As we discuss above, we avoid associating these sites with either agricultural or pastoral subsistence strategies. We recognize that such classifications are difficult, even in cases of large urban centers in rich agricultural areas. Our modelling of these settlements patterns as conforming to homogenously agricultural or pastoral subsistence strategies is therefore meant to test the applications of such definitions of suitability and identify deviances.

We employ NDVI as a proxy for agricultural suitability, with the assumption that areas with high values are those which are best suited for agriculture. While NPP is the more popular proxy for suitability in applications of IDMs (e.g. Allen et al. 2016; Coddington and Jones 2013; Giovas and Fitzpatrick 2014; Jazwa and Jazwa 2017), in our case the available data was incomplete and missing for several parts of the study area, particularly those areas that are today desert. Though NDVI and NPP are derived differently and have some differences, they are well correlated and for our purposes NDVI was sufficient (Xu et al. 2012). To measure NDVI, we calculated the mean annual values for the study region based on 16-day composites collected by the Moderate Resolution Imaging Spectroradiometer (MOD13A2.006 product: 1 km resolution) from NASA's Terra satellite (Didan 2015). These images were collected in 2018 and processed in Google Earth Engine (Gorelick et al. 2017). Because these data are modern, they reflect the distribution of agricultural land today, which may not have been the case in the past. The long-term use of irrigation canals in many of these areas, however, suggests that in most cases sites with high NDVI values today will have had similar ones in the past (Fouache et al. 2012; Wordsworth 2018).

As with NPP, however, there are no intrinsic qualities to these data that make them objectively appropriate for agricultural production specifically. That is, NDVI values measure the health of vegetation, which can be interpreted as indicative of the productivity of agricultural areas (e.g. Bellón et al. 2019; Eckert et al. 2017) but can also be used to rank suitability for pastoral strategies. Indeed, NDVI is employed by Moritz et al. (2013) in their study of mobile pastoralists in the Logone floodplain of Cameroon, where high NDVI values are used as a proxy for suitability. Honeychurch and Amartuvshin (2007) likewise utilize mean NDVI values of tributary valley zones to explore the relationship between density of settlements and high pastoral productivity. Given that our study considers both agricultural and pastoral suitability, it is necessary to elaborate on why NDVI is not used for both or for the latter.

Visual inspection of the mean annual NDVI image ([Fig. 2a](#)) highlights clearly the starkness with which agricultural land is distinguished from the surrounding landscape. River channels and valleys appear green while the steppe, desert, and mountainous areas appear as varying shades of red. The distinction between these microenvironments is clearer on the north side of the Amu Darya river, where the ongoing effects of Soviet irrigation projects clearly differentiate the historical legacies on both sides of the border ([Kreutzmann 2016](#); [Pravilova 2009](#)). We therefore employ NDVI as a measure of agricultural suitability due to the effectiveness with which it highlights these environmental differences and because of its clear association with areas that are today agriculturally productive. Though pastoral activity would likely have taken place in these areas as well, ethnographic and archaeological research has identified access to upland pastures where herds can graze in the summers as an essential component of transhumant pastoral strategies in this region ([Masanov 1995](#); [Stark et al. 2010](#)), which is not adequately captured by NDVI.

For this reason, we employ elevation as a proxy for pastoral suitability ([Fig. 2b](#)). The nature of pastoral mobility requires access to lowlands as well, however, as summer pastures become inaccessible in the winters. Thus, we sample all elevation values within a 10 km buffer around each site and measure the standard deviation of elevation values (ESD) within this area. High standard deviations will indicate access to both upland and lowland areas, which we define as most suitable for pastoral subsistence strategies. Though pastoralists certainly can and do travel more than 10 km in search of pastures, we retain this value as a conservative measure of how ideally sites are located in respect to different ecological zones ([Frachetti 2008: 27](#); [Kerven et al. 2011](#)). Elevation values were derived from a digital elevation model (DEM) produced by the Shuttle Radar Topography Mission (SRTM V3 Product) ([Farr 2007](#)), queried and resampled to a resolution of 250 m in Google Earth Engine ([Gorelick et al. 2017](#)).

Methods

Having collected and processed the relevant NDVI and elevation data, we extracted values for each site and conducted subsequent analyses in R ([R Core Team 2019](#); see [Supplemental Material](#)). Both DVI and ESD are intentionally simplistic proxies for suitability that we employ, in conjunction, to model the presumed motivations determining the distribution of settlement in response to both agricultural and pastoral perceptions of suitability. While we are unable to measure the *basic suitability* of these habitats, that is, the fitness of the first occupant to settle there ([Fretwell and Lucas 1969: 83](#)), we can rank them in order of their first settlement and measure their duration of occupation through time. Duration here is measured in terms of number of periods rather than years, since that is the nature of the chronological data provided for each site ([Ball 1982: 15-16](#)). All periods are roughly 100 years long, with the exception of the Bronze and Iron Ages, which we exclude from analysis of duration for this reason. These metrics are sufficient for us to test two of our predictions, that habitats settled first will be the most suitable and that the most suitable habitats will be occupied longest. To test for statistically significant difference between periods, for both predictions we conduct Kruskal-Wallis (KW) tests on both the NDVI and ESD data, with post hoc Pairwise Wilcoxon Rank Sum tests.

To test the third prediction, that the average suitability of a settlement pattern should decrease as sites increase in number, we use linear regression to model suitability against site count per period. Because our data does not contain any demographic information, we employ site count as a proxy. An increase in site count is taken to reflect a general increase in population

and negative density dependencies that cause individuals to move to lower ranked habitats. While recent research has shown strong correlations between population proxies such as site count, site size, and summed radiocarbon probability distributions, deviations do occur in cases of settlement nucleation or dispersal (Palmisano et al. 2017). That is, a decrease in site count need not necessarily reflect decreases in population if greater numbers of people are living in those sites. This is clearly a problem for the purposes of our study, but one which we do not believe changes the overall conclusions of our analysis.

To explore these trends further and strengthen our interpretation, we also create kernel density plots of values for each period according to each suitability proxy. These allow us to examine the overall distribution of values and note instance of multimodality as well as to compare these distributions through time. Similarly, we compare the distribution of sites against a random sample of points within the region to test whether the distribution of values samples at the sites are the result of random chance (Jarosław and Hildebrandt-Radke 2009). These distributions are likewise tested for statistical difference, in this case using a two-sample Kolmogorov-Smirnov (KS) test.

Results

Beginning with agricultural suitability as measured by NDVI values, our results show that the first prediction of IDMs, that habitats settled first will be the most suitable, cannot be satisfied when using NDVI or ESD as measures of suitability. Suitability is relatively low in the Bronze and Iron Ages and drastically increases beginning in the Achaemenid period, at which point it decreases slightly and remains more or less constant for the remainder of the periods (Fig. 3a). Likewise, investigating pastoral suitability by ESD shows similar patterns. Suitability is again lower in the earliest periods and increases steadily through time (Fig. 3b). KW tests show that in both cases the distribution of NDVI and ESD values significantly differ by period (NDVI: Chi square = 70, $p < 0.001$, $df = 19$; ESD: Chi square = 73, $p < 0.001$, $df = 19$). Pairwise Wilcoxon rank sum tests further show that, for NDVI, the distribution of values from the first two periods (the Bronze and Iron Ages) are statistically different ($p < 0.05$) from almost every later period, allowing us to conclude that these earlier sites were indeed in lower NDVI areas than later sites. For ESD, the distribution of values from the the Bronze Age are not statistically different ($0.051 < p < 0.3$) from all the later periods but are significantly different ($p < 0.001$) than ESD distributions from the Turkish Khanate to Ghurid periods, during which mean ESD is highest. This suggests that in the case of pastoral suitability, earlier sites were indeed lower in ESD values than later sites. Tables with the all p-values for each pairwise Wilcoxon test can be found in the supplemental material.

For the second prediction, that the most suitable habitats will be occupied longest, boxplot diagrams of NDVI values according to quartile groupings by duration show that this seems to be the case (Fig. 4a). Those sites occupied longest are those that have, on average, the highest NDVI values. This is not the case for pastoral suitability, where duration seems to have no relationship with suitability and all quartiles show similar suitability ranges (Fig. 4b). KW tests confirm that the distribution of NDVI values significantly differ by period (NDVI: Chi square = 68, $p < 0.001$, $df = 3$), while ESD values do not (ESD: Chi square = 7, $p = 0.07$, $df = 3$). Pairwise Wilcoxon rank sum tests further support these conclusions, showing that sites in the quartile with the longest duration have NDVI values statistically different ($p < 0.05$) from those in quartile one and three, though not quartile two ($p < 0.095$). Tables with the p-values for each pairwise Wilcoxon test can again be found in the supplemental material.

For the third prediction, that the average suitability of a settlement pattern should decrease as sites increase in number, linear regression models of mean NDVI values against site numbers shows suitability in fact increases with site count per period, rather than decreases (Fig. 5a). The same trend holds for pastoral suitability, with increasing numbers of sites showing increases in the standard deviation of elevation values (Fig. 5b). Both suitability proxies show moderately strong and statistically significant correlations with site count (NDVI: $R^2 = 0.46$, $p < 0.001$; ESD: $R^2 = 0.63$, $p < 0.001$). Thus, with the exception of sites with high NDVI values being occupied longest (Fig. 4a), our results do not allow us to accept the predictions of IDMs.

Looking at the kernel density plots for each period (Fig. 6-7), apparent in many is a multimodal distribution that, during different periods, is more or less pronounced. For the agricultural suitability density plots (Fig. 6), we note a sharp reversal between the Iron Age (I) and the Achaemenid (A) periods, showing a shift from sites with low NDVI values to sites with high NDVI values. From the Seleucid (SE) period onwards, this peak of high NDVI values remains, but is generally balanced by peaks of lower NDVI values that are at times just as prominent, such as during the Graeco-Bactrian (G1, G2) and Samanid (S) periods. Looking at the pastoral suitability density plots (Fig. 7), a second peak of ESD values is also evident, though at far lower densities than the first peak which is constant through time. Even so, beginning in the Kushan periods (K1, K2), this second peak persists and is more or less constant for the remainder of the periods. For both suitability density plots, the second peak should correspond to areas that are most suitable, yet in both cases these peaks often show lower density than the first peaks. In both cases, it is the first peak that is most consistent and most pronounced, suggesting that areas of relatively low NDVI and elevation variability are most consistently preferred. Comparison of overall site suitabilities against random point patterns shows that peaks in both suitability plots are the result of deliberate settlement rather than random chance (Fig. 8), which KS tests also indicate (NDVI: $D = 0.4$, $p < 0.001$; ESD: $D = 0.3$, $p < 0.001$).

Discussion

As Winterhalder and Kennett (2006: 17) wrote more than ten years ago, “The likelihood that the better foraging and farming sites have non-overlapping distributions, and the implied changes in mobility and sedentism...offers fertile ground for exploration.” While we have focused here on pastoral and farming strategies rather than foraging, the fundamental suggestion Winterhalder and Kennett provided was that different subsistence strategies have different requirements and therefore different perceptions of suitability. In testing this suggestion, we have explored the extent to which a single index of suitability can be applied in cases where mixed subsistence strategies are practiced by heterogeneous elements of regional populations. Our results indicate that neither agricultural nor pastoral measures of suitability, as we have defined them, sufficiently model the distribution of sites in Bactria or their changes through time according to IDMs.

While we have acknowledged certain limitations of the data and recognize that, in testing the assumptions of these IDMs we have made many of our own, the data do overall reflect the historical trends and processes that others have argued took place in the region. The increase in mean NDVI likely reflects the expansion of irrigation infrastructure and increasing settlement within the oases of Bactria that other lines of evidence have shown to be taking place beginning in the Achaemenid period (Francfort and Lecomte 2002; Wu et al. 2015). Likewise, the emergence of a second peak in the pastoral suitability plots beginning with the Kushan period may indicate a greater emphasis on pastoral practices that appears at the same time that the

region is incorporated into nomadic states (Asimov and Bosworth 1998). The persistently high number of sites in both low NDVI and low elevation standard deviation areas—those within the first peaks of the density plots—shows that neither irrigated agriculture nor pastoralism were the only or primary subsistence practices taking place.

Though we cannot conclusively demonstrate that sites with low NDVI values were directed towards pastoralism, such identification would reinstate the assumptions about suitability we have intentionally, for the purposes of testing, taken. As our results show, those sites that were lower ranked according to agricultural suitability—those within the first peaks—are not the sites that are within the second peak according to pastoral suitability. That is, there are not two independent settlement patterns dictated by “non-overlapping” perceptions of suitability. There is overlap, which research on agropastoral communities is increasingly showing and highlighting as fundamental to life in this region (Brite et al. 2017; Frachetti 2012; Honeychurch and Makarewicz 2016; Stride et al. 2009; Wu et al. 2015). Settlement patterning instead seems to reflect a kind of compromise between the preferences of agricultural and pastoral societies, with the most settled areas seemingly being those that afforded the best compromise between agricultural production and upland resources suited to a mixed agropastoral economy, rather than areas that suited one over the other.

As we stated at the outset of this study, it is not the fundamental predictions of IDMs themselves that we are testing here, but rather the assumptions about suitability that determine their application. Should we define suitability as a weighted combination of variables relevant to agricultural and pastoral subsistence practices, it is likely that the settlement data would conform better to IDMs. Indeed, it is certainly possible that the patterns evident in our data do in fact conform to an ideal distribution, by which the densely packed areas of the second density peaks contain greater populations than the more numerous sites of the first peak. One might expect this based on the generally higher population density of agriculturally-focused settlements as compared to pastoral nomadic sites (Ur and Hammer 2009). As discussed, further demographic data is necessary to clarify this question.

A broader point, however, is that habitat suitability can change due to factors besides population density. The expansion or intensification of irrigation infrastructure throughout the Achaemenid, Seleucid, and Greco-Bactrian periods demonstrates how habitat suitability can increase through ecological engineering. That those sites occupied first are those with relatively low NDVI values perhaps reflects the role of this kind of landesque capital in encouraging settlement. That those sites occupied longest are those with the highest NDVI values likewise may show the continued investment in and inheritance of landscape modifications (Morrison 2015; Quintus and Cochrane 2018). These irrigation canals required upkeep and maintenance, as canals silt up and watercourses change due to both natural (tectonic) and sociopolitical forces (water management systems) (Fouache et al. 2012). The abandonment or expansion of settlement in certain areas is related to these processes (Wordsworth 2018), which may also explain the changing density of sites within the first peaks of the NDVI density plots through time. Thus, in addition to changing as a result of increases or decreases in population density, suitability may also change due to long-term depletion, by which resources are reduced due to habitat degradation through time (McClure et al. 2006; Sutherland 1996).

As this paper has shown, the use of IDMs as “simple heuristics to delineate a question and organize hypotheses about different suites of trade-offs” (Coddington and Bird 2015: 11) has allowed us to investigate how subsistence economies intersect with sociopolitical changes and on-going relationships between people and the land. In identifying deviations from the

predictions of the models, we have been able to highlight periods of pronounced change and reorganization, and continuity, that reflect the sociopolitical changes taking place in the region. While further work is necessary to explore the patterns identified in the data here, the growing popularity of IDMs and their increasing application to non-hunter-gatherer populations warrants more discussion about the ways in which suitability is being defined and whether we can effectively study the relationship between population and settlement location based on a single definition. For the many IDM papers published in the past 50 years, a single definition of suitability seems to work well, at least for constant and homogenous subsistence economies. Yet the prevailing assumptions of these models about individual fitness and habitat suitability should apply just as well in cases of changing and heterogeneous subsistence economies. If IDMs are to be applied more broadly, further work on these kinds of subsistence economies will be necessary.

Acknowledgements

We would like to thank Elic Weitzel and Brian Coddling for inviting us to the SAA session in which this paper was first presented. We would also like to thank Warwick Ball and Anthony Lauricella for their help in obtaining the gazetteer data, and the two anonymous reviewers for the helpful feedback and suggestions.

Disclosure statement: No potential conflict of interest was reported by the authors.

Bibliography

- Alizadeh, Abbas. 2010. "The Rise of the Highland Elamite State in Southwestern Iran." *Current Anthropology* 51 (3): 353–83. <https://doi.org/10.1086/652437>.
- Allen, Mark W., Robert Lawrence Bettinger, Brian F. Coddling, Terry L. Jones, and Al W. Schwitalla. 2016. "Resource Scarcity Drives Lethal Aggression among Prehistoric Hunter-Gatherers in Central California." *Proceedings of the National Academy of Sciences* 113 (43): 12120–25. <https://doi.org/10.1073/pnas.1607996113>.
- Asimov, M. S., and Clifford E. Bosworth. eds. 1998. *History of Civilizations of Central Asia: The Age of Achievement: A.D. 750 to the End of the Fifteenth Century Part One: The Historical, Social and Economic Setting*. Vol. IV. Paris: UNESCO Publishing.
- Ball, Warwick. 1982. *Archaeological Gazetteer of Afghanistan*. Paris: Recherche sur les civilisations.
- Ball, Warwick. 2019. *Archaeological Gazetteer of Afghanistan: revised edition*. Oxford: Oxford University Press.
- Ball, Warwick, and Norman Hammond. 2019. *The Archaeology of Afghanistan: From Earliest Times to the Timurid Period: New Edition*. Edinburgh: Edinburgh University Press.
- Barnard, Hans, and Willeke Wendrich. 2008. *The archaeology of mobility: old world and new world nomadism*. Los Angeles: Cotsen Institute of Archaeology at UCLA.
- Bellón, Beatriz, Agnès Bégué, Danny Lo Seen, Claudio de Almeida, and Margareth Simões. 2019. "A Remote Sensing Approach for Regional-Scale Mapping of Agricultural Land-Use Systems Based on NDVI Time Series." *Remote Sensing* 9, no. 6: 600. <https://doi.org/10.3390/rs9060600>.
- Brite, Elizabeth Baker, Gairatdin Khozhaniyazov, John M. Marston, Michelle Negus Cleary, and Fiona J. Kidd. 2017. "Kara-Tepe, Karakalpakstan: Agropastoralism in a Central Eurasian Oasis in the 4th/5th Century A.D. Transition." *Journal of Field Archaeology* 42 (6): 514–29. <https://doi.org/10.1080/00934690.2017.1365563>.
- Chang, Claudia. 2018. *Rethinking prehistoric Central Asia: shepherds, farmers, and nomads*. New York: Routledge.
- Coddling, Brian F., and Terry L. Jones. 2013. "Environmental Productivity Predicts Migration, Demographic, and Linguistic Patterns in Prehistoric California." *Proceedings of the National Academy of Sciences* 110 (11): 14569–73. <https://doi.org/10.1073/pnas.1302008110>.

- 515 Coddington, Brian F., and Douglas W. Bird. 2015. "Behavioral Ecology and the Future of
516 Archaeological Science." *Journal of Archaeological Science* 56: 9–20.
517 <https://doi.org/10.1016/j.jas.2015.02.027>.
- 518 Cribb, Joe, and Georgina Herrmann. eds. 2009. *After Alexander: Central Asia before Islam*.
519 Oxford: Oxford University Press.
- 520 Cribb, Roger. 1991. *Nomads in Archaeology*. Cambridge: Cambridge University Press.
- 521 Dani, Ahmad Hasan, and V. M. Masson. 1992. "Introduction." In *History of civilizations of*
522 *Central Asia. Volume 1. The dawn of civilization: earliest times to 700 B.C.*, edited by
523 Ahmad Hasan Dani and V. M. Masson, 19–28. Paris: UNESCO Publishing.
524
- 525 Derevyanko, Anatoly P., and Lü Zun-E. 1992. "Upper Paleolithic Cultures." In *History of*
526 *civilizations of Central Asia. Volume 1. The dawn of civilization: earliest times to 700*
527 *B.C.*, edited by Ahmad Hasan Dani and V. M. Masson, 89–108. Paris: UNESCO
528 Publishing.
529
- 530 Didan, K. 2015. *MOD13A2 MODIS/Terra Vegetation Indices 16-Day L3 Global 1km SIN Grid*
531 *V006* [Data set]. NASA EOSDIS Land Processes DAAC. doi:
532 [10.5067/MODIS/MOD13A2.006](https://doi.org/10.5067/MODIS/MOD13A2.006)
- 533 Eckert, Sandra, Boniface Kiteme, Evanson Njuguna, and Julie Zaehring. 2017. "Agricultural
534 Expansion and Intensification in the Foothills of Mount Kenya: A Landscape Perspective."
535 *Remote Sensing* 9, no. 8: 784–804. <https://doi.org/10.3390/rs9080784>.
- 536 Farr, Tom G., Paul A. Rosen, Edward Caro, Robert Crippen, Riley Duren, Scott Hensley,
537 Michael Kobrick, et al. 2007. "The Shuttle Radar Topography Mission." *Reviews of*
538 *Geophysics* 45 (2): RG2004. <https://doi.org/10.1029/2005RG000183>.
- 539 Fouache, Eric, Roland Besenval, Claude Cosandey, Céline Coussot, Matthieu Ghilardi, Sébastien
540 Huot, and Michel Lamothe. 2012. "Palaeochannels of the Balkh River (Northern
541 Afghanistan) and Human Occupation since the Bronze Age Period." *Journal of*
542 *Archaeological Science* 39 (11): 3415–27. <https://doi.org/10.1016/j.jas.2012.05.030>.
- 543 Frachetti, Michael D. 2008. *Pastoralist Landscapes and Social Interaction in Bronze Age*
544 *Eurasia*. Berkeley: University of California Press.
- 545 Frachetti, Michael D. 2012. "Multiregional Emergence of Mobile Pastoralism and Nonuniform
546 Institutional Complexity across Eurasia." *Current Anthropology* 53 (1): 2–38.
547 <https://doi.org/10.1086/663692>.
- 548 Frachetti, Michael D., and Farhod Maksudov. 2014. "The Landscape of Ancient Mobile
549 Pastoralism in the Highlands of Southeastern Uzbekistan, 2000 B.C.–A.D. 1400." *Journal*
550 *of Field Archaeology* 39 (3): 195–212.
551 <https://doi.org/doi:10.1179/0093469014Z.000000000085>.

- 552 Francfort, Henri-Paul, and Olivier Lecomte. 2002. "Irrigation et Societe En Asie Centrale Des
553 Origines a l'epoque Achemenide." *Annales. Histoire, Sciences Sociales* 57: 625–63.
- 554 Fretwell, Stephen D., and Henry L. Lucas Jr. 1969. "On territorial behavior and other factors
555 influencing habitat distribution in birds. I. Theoretical development." *Acta Biotheoretica*
556 19: 16–36.
- 557 Gardin, Jean-Claude. 1998. *Prospections archéologiques en Bactriane orientale (1974– 1978).*
558 *Vol. 3, Description des sites et notes de synthèse. Mémoires de la Mission Archéologique*
559 *Française en Asie Centrale, vol. 9.* Paris: Éditions Recherche sur les Civilisations.
- 560 Giovas, Christina M., and Scott M. Fitzpatrick. 2014. "Prehistoric Migration in the Caribbean:
561 Past Perspectives, New Models and the Ideal Free Distribution of West Indian
562 Colonization." *World Archaeology* 46 (4): 569–89.
563 <https://doi.org/10.1080/00438243.2014.933123>.
- 564 González-Ruibal, Alfredo, and Jorge de Torres. 2018. "The Fair and the Sanctuary: Gathering
565 Places in a Nomadic Landscape (Somaliland, 1000–1850 AD)." *World Archaeology* 50 (1):
566 23–40. <https://doi.org/10.1080/00438243.2018.1489735>.
- 567 Gorelick, Noel, Matt Hancher, Mike Dixon, Simon Ilyushchenko, David Thau, and Rebecca
568 Moore. 2017. "Google Earth Engine: Planetary-Scale Geospatial Analysis for Everyone."
569 *Remote Sensing of Environment* 202: 18–27. <https://doi.org/10.1016/j.rse.2017.06.031>.
- 570 Harmatta, János, B.N. Puri, and G.F. Etemadi, eds. 1996. *History of Civilizations of Central Asia*
571 *- The Development Sedentary and Nomadic Civilizations: 700 B.C. to A.D. 250.* Vol. II.
572 Paris: UNESCO Publishing.
- 573 Honeychurch, William. 2014. "Alternative Complexities: The Archaeology of Pastoral Nomadic
574 States." *Journal of Archaeological Research* 22 (4): 277–326.
575 <https://doi.org/10.1007/s10814-014-9073-9>.
- 576 Honeychurch, William, and Chunag Amartuvshin. 2007. "Hinterlands, Urban Centers, and
577 Mobile Settings: The 'New' Old World Archaeology from the Eurasian Steppe." *Asian*
578 *Perspectives* 46 (1): 36–64. <https://doi.org/10.1353/asi.2007.0005>.
- 579 Honeychurch, William, and Cheryl A. Makarewicz. 2016. "The Archaeology of Pastoral
580 Nomadism." *Annual Review of Anthropology* 45: 341–59. <https://doi.org/10.1146/annurev-anthro-102215-095827>.
- 582 Jarosław, Jasiewicz, and Iwona Hildebrandt-Radke. 2009. "Using Multivariate Statistics and
583 Fuzzy Logic System to Analyse Settlement Preferences in Lowland Areas of the Temperate
584 Zone: An Example from the Polish Lowlands." *Journal of Archaeological Science* 36 (10):
585 2096–2107. <https://doi.org/10.1016/j.jas.2009.06.004>.

- 586 Jazwa, Christopher S., and Kyle A. Jazwa. 2017. "Settlement Ecology in Bronze Age Messenia."
587 *Journal of Anthropological Archaeology* 45: 157–69.
588 <https://doi.org/10.1016/j.jaa.2016.12.003>.
- 589 Kennett, Douglas, Atholl Anderson, and Bruce Winterhalder. 2006. "The Ideal Free Distribution,
590 Food Production and the Colonization of Oceania." In *Behavioral Ecology and the*
591 *Transition to Agriculture*, edited by Douglas Kennett and Bruce Winterhalder, 265–288.
592 Los Angeles: University of California Press.
- 593 Kerven, Carol, Bernd Steimann, Laurie Ashley, Chad Dear, and Inam ur Rahim. 2011.
594 *Pastoralism and Farming in Central Asia's Mountains: A Research Review. MSRC*
595 *Background Paper No. 1*. University of Central Asia.
- 596 Khazanov, Anatoly M. 1994. *Nomads and the Outside World. Second Edition*. Madison:
597 University of Wisconsin Press.
- 598 Kidd, Fiona, and Sören Stark. 2019. "Urbanism in Antique Sogdiana? A View from the Bukhara
599 Oasis." In *Urban Cultures of Central Asia from the Bronze Age to the Karakhanids*, edited
600 by Christoph Baumer and Mirko Novák, 163–83. Weisbaden: Harrassowitz Verlag.
- 601 Kohl, Philip L. 2007. *The Making of Bronze Age Eurasia*. Cambridge: Cambridge University
602 Press.
- 603 Kramer, Andrew M., Brian Dennis, Andrew M. Liebhold, and John M. Drake. 2009. "The
604 Evidence for Allee Effects." *Population Ecology* 51 (3): 341–54.
605 <https://doi.org/10.1007/s10144-009-0152-6>.
- 606 Kreutzmann, Hermann. 2016. "From Upscaling to Rescaling—The Fergana Basin's
607 Transformation from Tsarist Irrigation to Water Management for an Independent
608 Uzbekistan." In *Society–Water–Technology: A Critical Appraisal of Major Water*
609 *Engineering Projects*, edited by Sebastian Hoechstetter, 113–127. Dordrecht: Springer.
- 610 Lambert, Patricia M., and Martin H. Welker. 2017. "Traumatic Injury Risk and Agricultural
611 Transitions: A View from the American Southeast and Beyond." *American Journal of*
612 *Physical Anthropology* 162(1): 120–42. <https://doi.org/10.1002/ajpa.23103>.
- 613 Lambert, Patricia M., and Martin H. Welker. 2019. "Revisiting Traumatic Injury Risk and
614 Agricultural Intensification: Postcranial Fracture Frequency at Cerro Oreja in the Moche
615 Valley of North Coastal Peru." *American Journal of Physical Anthropology* 169(1): 143–
616 51. <https://doi.org/10.1002/ajpa.23801>.
- 617 Leriche, Pierre. 2009. "Bactria, Land of a Thousand Cities." In *After Alexander: Central Asia*
618 *before Islam*, edited by Joe Cribb and Georgina Herrmann, 121–154. Oxford: Oxford
619 University Press.

- 620 Litvinsky, B. A., Zhang Guang-da, and R. Shabani Samghabadi. 1996. *History of Civilizations of*
621 *Central Asia: The Crossroads of Civilizations: A.D. 250 to 750*. Vol. III. Paris: UNESCO
622 Publishing.
- 623 Liu, Xinru. 2001. "Migration and Settlement of the Yuezhi- Kushan: Interaction and
624 Interdependence." *Journal of World History* 12 (2): 261–92.
- 625 Mairs, Rachel. 2014. *The Hellenistic Far East: Archaeology, Language, and Identity in Greek*
626 *Central Asia*. Oakland: University of California Press.
- 627 Masanov, N. 1995. "Northern Areas (Transoxania and the Steppes) Pastoral Production," in
628 *History of Civilizations of Central Asia: Development in Contrast: From the Sixteenth to*
629 *the Mid- nineteenth Century*, edited by K. M. Baipakov, S. Moosvi, and A. Burton, 373-
630 375. New Delhi: UNESCO Publishing.
- 631 McClure, Sarah B., Michael A. Jochim, and C. Michael Barton. 2006. "Human Behavioral
632 Ecology, Domestic Animals, and Land Use During the Transition to Agriculture in
633 Valencia, Eastern Spain." In *Behavioral Ecology and the Transition to Agriculture*, edited
634 by Douglas J. Kennett and Bruce Winterhalder, 197–216. Berkeley: University of California
635 Press.
- 636 McClure, Sarah B., C. Michael Barton, and Michael A. Jochim. 2009. "Human Behavioral
637 Ecology, Domestic Animals, and Land Use During the Transition to Agriculture in
638 Valencia, Eastern Spain." *Journal of Anthropological Research* 65 (2): 253–69.
- 639 Miller, Bryan K., Martin Furholt, Jamsranjav Bayarsaikhan, Tömörbaatar Tüvshinjargal, Lennart
640 Brandtstätter, Joshua Wright, Tseel Ayush, and Tina Wunderlich. 2019. "Proto-Urban
641 Establishments in Inner Asia: Surveys of an Iron Age Walled Site in Eastern Mongolia."
642 *Journal of Field Archaeology* 44 (4): 267–86.
643 <https://doi.org/10.1080/00934690.2019.1598170>.
- 644 Miller, Naomi F. 2003. "The use of plants at Anau North." In *A Central Asian village at the*
645 *dawn of civilization, excavations at Anau, Turkmenistan*, edited by Fredrick T. Hiebert and
646 Kakamurad Kurdansakhatov, 201–215. Philadelphia: University of Pennsylvania Museum.
- 647 Moritz, Mark, Ian M. Hamilton, Yu-Jen Chen, and Paul Scholte. 2013. "Mobile Pastoralists in
648 the Logone Floodplain Distribute Themselves in an Ideal Free Distribution." *Current*
649 *Anthropology* 55 (1): 115–22. <https://doi.org/10.1086/674717>.
- 650 Morrison, Kathleen D. 2015. "Archaeologies of Flow: Water and the Landscapes of Southern
651 India Past, Present, and Future." *Journal of Field Archaeology* 40 (5): 560–80.
652 <https://doi.org/10.1179/2042458215Y.0000000033>.
- 653 Motuzaite Matuzeviciute, G., E. Lightfoot, T. C. O'Connell, D. Voyakin, X. Liu, V. Loman, S.
654 Svyatko, E. Usmanova, and M. K. Jones. 2015. "The Extent of Cereal Cultivation among
655 the Bronze Age to Turkic Period Societies of Kazakhstan Determined Using Stable Isotope

- 656 Analysis Ofbone Collagen.” *Journal of Archaeological Science* 59: 23–34.
657 <https://doi.org/10.1016/j.jas.2015.03.029>.
- 658 Palmisano, Alessio, Andrew Bevan, and Stephen Shennan. 2017. “Comparing Archaeological
659 Proxies for Long-Term Population Patterns: An Example from Central Italy.” *Journal of*
660 *Archaeological Science* 87: 59–72. <https://doi.org/10.1016/j.jas.2017.10.001>.
- 661 Peake, Harold, and H. J. Fleure. 1928. *The steppe and the sown*. London: Yale University Press.
- 662 Pravilova, Ekaterina. 2009. “River of Empire: Geopolitics, Irrigation, and the Amu Darya in the
663 Late XIXth Century.” *Cahiers d’Asie Centrale* 17 (18): 255–87.
- 664 Pufer, Keith M., Amy E. Thompson, Clayton R. Meredith, Brendan J. Culleton, Jillian M.
665 Jordan, Claire E. Ebert, Bruce Winterhalder, and Douglas J. Kennett. 2017. “The Classic
666 Period Maya Transition from an Ideal Free to an Ideal Despotic Settlement System at the
667 Polity of Uxbenká.” *Journal of Anthropological Archaeology* 45: 53–68.
668 <https://doi.org/10.1016/j.jaa.2016.11.003>.
- 669 Quintus, Seth, and Ethan E. Cochrane. 2018. “The Prevalence and Importance of Niche
670 Construction in Agricultural Development in Polynesia.” *Journal of Anthropological*
671 *Archaeology* 51 (June): 173–86. <https://doi.org/10.1016/j.jaa.2018.06.007>.
- 672 R Core Team. 2019. R: A language and environment for statistical computing. R Foundation for
673 Statistical Computing. Vienna, Austria. <https://www.R-project.org/>.
- 674 Rouse, Lynne M., and Barbara Cerasetti. 2017. “Micro-Dynamics and Macro-Patterns:
675 Exploring New Archaeological Data for the Late Holocene Human-Water Relationship in
676 the Murghab Alluvial Fan, Turkmenistan.” *Quaternary International* 437: 20–34.
677 <https://doi.org/10.1016/j.quaint.2015.12.021>.
- 678 Rouse, Lynne M., and Barbara Cerasetti. 2018. “Mixing Metaphors: Sedentary-Mobile
679 Interactions and Local-Global Connections in Prehistoric Turkmenistan.” *Antiquity* 92
680 (363): 674–89. <https://doi.org/10.15184/aqy.2018.88>.
- 681 Salvatori, Sandro. 2008. “The Margiana settlement pattern from the Middle Bronze Age to the
682 Parthian-Sasanian: a contribution to the study of complexity.” In *The Bronze Age and Early*
683 *Iron Age in the Margiana lowlands: facts and methodological proposals for a redefinition*
684 *of the research strategies*, edited by Sandro Salvatori, Maurizio Tosi and Barbara Cerasetti,
685 57–74. Oxford: Archaeopress.
- 686 Sarianidi, Viktor. 1992. “Food-producing and other Neolithic communities in Khorasan and
687 Transoxania: eastern Iran, Soviet Central Asia and Afghanistan.” In *History of civilizations*
688 *of Central Asia. Volume 1. The dawn of civilization: earliest times to 700 B.C.*, edited by
689 Ahmad Hasan Dani and V. M. Masson, 109–126. Paris: UNESCO Publishing.
- 690 Sarianidi, Viktor I. 2005. *Gonur-Depe: gorod tsareĭ bogov*. Ashgabat: Miras.

- 691 Soucek, Svat. 2000. *A History of Inner Asia*. Cambridge: Cambridge University Press.
- 692 Spengler, Robert N., and George Willcox. 2013. "Archaeobotanical Results from Sarazm,
693 Tajikistan, an Early Bronze Age Settlement on the Edge: Agriculture and Exchange."
694 *Environmental Archaeology* 18 (3): 211–21.
695 <https://doi.org/10.1179/1749631413y.00000000008>.
- 696 Spengler, Robert. N, Claudia Chang, and Perry A. Tourtellotte. 2013. Agricultural production in
697 the Central Asian mountains: Tuzusai, Kazakhstan (410-150 B.C.). *Journal of Field*
698 *Archaeology*, 38(1), 68–85. <https://doi.org/10.1179/0093469012Z.000000000037>
- 699 Spengler, Robert, Michael Frachetti, Paula Doumani, Llynne Rouse, Barbara Cerasetti, Elissa
700 Bullion, and Alexei Mar'yashev. 2014. "Early Agriculture and Crop Transmission among
701 Bronze Age Mobile Pastoralists of Central Eurasia." *Proceedings of the Royal Society B:*
702 *Biological Sciences* 281 (April): 20133382. <https://doi.org/10.1098/rspb.2013.3382>.
- 703 Spengler, Robert N., Naomi F. Miller, Reinder Neef, Perry A. Tourtellotte, and Claudia Chang.
704 2017. "Linking Agriculture and Exchange to Social Developments of the Central Asian Iron
705 Age." *Journal of Anthropological Archaeology* 48 (May): 295–308.
706 <https://doi.org/10.1016/j.jaa.2017.09.002>.
- 707 Spengler, Robert N. 2015. Agriculture in the Central Asian Bronze Age. *Journal of World*
708 *Prehistory*, 28(3), 215–253. <https://doi.org/10.1007/s10963-015-9087-3>
- 709 Stark, Sören, Usman Eshonkulov, Matthias Gütte, and Nabidzhon Rakhimov. 2010. "Resource
710 Exploitation and Settlement Dynamics in High Mountain Areas. The Case of Mediaeval
711 Ustrūshana (Northern Tadzhikistan)." *Archaeologische Mitteilungen Aus Iran Und Turan* 42:
712 67–85.
- 713 Stride, Sebastian. 2004a. "An Archaeological GIS of the Surkhan Darya Province (Southern
714 Uzbekistan)." *Silk Road Newsletter* 3 (1): 30–34.
- 715 Stride, Sebastian. 2004b. *Géographie Archéologique de La Province Du Surkhan Darya. Volume*
716 *III: Catalogue Des Sites*. Université Paris I Panthéon-Sorbonne.
- 717 Stride, Sebastian. 2009. "Regions and Territories in Southern Central Asia: What the Surkhan
718 Darya Province Tells Us about Bactria." In *After Alexander: Central Asia before Islam*,
719 edited by Joe Cribb and Georgina Herrmann, 99–120. Oxford: Oxford University Press.
- 720 Stride, Sebastian, Bernardo Rondelli, and Simone Mantellini. 2009. "Canals versus Horses:
721 Political Power in the Oasis of Samarkand." *World Archaeology* 41 (1): 73–87.
722 <https://doi.org/10.1080/00438240802655302>.
- 723 Sutherland, William J. 1996. *From Individual Behaviour to Population Ecology*. Oxford: Oxford
724 University Press.

- 725 Taylor, William, Svetlana Shnaider, Aida Abdykanova, Antoine Fages, Frido Welker, Franziska
726 Irmer, Andaine Seguin-Orlando, et al. 2018. "Early Pastoral Economies along the Ancient
727 Silk Road: Biomolecular Evidence from the Alay Valley, Kyrgyzstan." *PLoS ONE* 13 (10):
728 1–19. <https://doi.org/10.1371/journal.pone.0205646>.
- 729 Tosi, Maurizio, Sadegh Malek Shamirzadi, and M. A. Joyenda. 1992. "The Bronze Age in Iran
730 and Afghanistan." In *History of civilizations of Central Asia. Volume 1. The dawn of*
731 *civilization: earliest times to 700 B.C.*, edited by Ahmad Hasan Dani and V. M. Masson,
732 191–224. Paris: UNESCO Publishing.
- 733 Tremayne, Andrew H., and Bruce Winterhalder. 2017. "Large Mammal Biomass Predicts the
734 Changing Distribution of Hunter-Gatherer Settlements in Mid-Late Holocene Alaska."
735 *Journal of Anthropological Archaeology* 45: 81–97.
736 <https://doi.org/10.1016/j.jaa.2016.11.006>.
- 737 Ur, Jason, and Emily Hammer. 2009. "Pastoral Nomads of the 2nd and 3rd Millennia A.D. on
738 the Upper Tigris River, Turkey: The Hirbemerdon Tepe Survey." *Journal of Field*
739 *Archaeology* 34 (1): 37–56. <https://doi.org/10.1179/009346909791071087>.
- 740 Weeks, L., C. M. Cable, K. A. Franke, S. Karacic, C. Newton, J. Roberts, I. Stepanov, et al.
741 2018. "Saruq Al-Hadid: A Persistent Temporary Place in Late Prehistoric Arabia." *World*
742 *Archaeology* 00 (00): 1–26. <https://doi.org/10.1080/00438243.2018.1491324>.
- 743 Winterhalder, Bruce. 2002. "Models." In *Darwin and Archaeology: A Handbook of Key*
744 *Concepts*, edited by John P. Hart and John Edward Terrell, 201–223. Westport, CT: Bergin
745 & Garvey.
- 746 Winterhalder, Bruce, Douglas J. Kennett, Mark N. Grote, and Jacob Bartruff. 2010. "Ideal Free
747 Settlement of California's Northern Channel Islands." *Journal of Anthropological*
748 *Archaeology* 29 (4): 469–90. <https://doi.org/10.1016/j.jaa.2010.07.001>.
- 749 Wordsworth, Paul. 2018. "The Hydrological Networks of the Balkh Oasis after the Arrival of
750 Islam: A Landscape Archaeological Perspective." *Afghanistan* 1 (1): 182–208.
751 <https://doi.org/10.3366/afg.2018.0010>.
- 752 Wu, Xin, Naomi F. Miller, and Pam Crabtree. 2015. "Agro-Pastoral Strategies and Food
753 Production on the Achaemenid Frontier in Central Asia: A Case Study of Kyzyltepa in
754 Southern Uzbekistan." *Iran* 53: 93–117. <https://doi.org/10.1080/05786967.2015.11834752>.
- 755 Xu, Chi, Yutong Li, Jian Hu, Xuejiao Yang, Sheng Sheng, and Maosong Liu. 2012. "Evaluating
756 the Difference between the Normalized Difference Vegetation Index and Net Primary
757 Productivity as the Indicators of Vegetation Vigor Assessment at Landscape Scale."
758 *Environmental Monitoring and Assessment* 184 (3): 1275–86.
759 <https://doi.org/10.1007/s10661-011-2039-1>.

760 Yaworsky, Peter M., and Brian F. Coddington. 2018. "The Ideal Distribution of Farmers:
761 Explaining the Euro-American Settlement of Utah." *American Antiquity* 83 (1): 75–90.
762 <https://doi.org/10.1017/aaq.2017.46>.

763

764 Table 1 - Periods into which the dataset is organized, with numbers of site per period (adapted
765 from Ball 1982: Appendix 2)

Abbreviation	Period	Date Range	Number of sites
B	Bronze Age	4000–1500 BCE	88
I	Iron Age	1500–700 BCE	78
A	Achaemenid	530–330 BCE	116
SE	Alexander/Seleucid	330–185 BCE	130
G1	Graeco-Bactrians (1)	250–185 BCE	135
G2	Graeco-Bactrians (2)	185–110 BCE	134
K1	Kushan 1	110 BCE–75 CE	233
K2	Kushan 2	75–275 CE	233
ES	Early Sasanians	275–345 CE	239
KS	Kushano-Sasanians	345–475 CE	236
H	Hephthalites (White Huns)	475–565 CE	206
LS	Later Sasanians	565–650 CE	211
T1	Turkish Khanates (1)	650–800 CE	205
T2	Turkish Khanates (2)	800–875 CE	204
SA	Samanids	875–1000 CE	236
GZ	Ghaznavids	1000–1050 CE	246
SL	Seljuks	1050–1150 CE	244
GH	Ghurids	1150–1220 CE	247
C	Chagatai Khanate	1330–1380 CE	6
TM	Timurids	1380–1500	121

766

768

769

770
771

772
773

Figure Captions

Figure 1: Map showing distribution of sites within northern Afghanistan.

Figure 2: Maps showing distribution of sites in relation to NDVI (a) and elevation (b).

Figure 3: Boxplot diagrams showing distribution of NDVI (a) and ESD values (b) by period.

Figure 4: Boxplot diagrams showing distribution of NDVI (a) and ESD values (b) by quartile groupings of site occupation duration.

Figure 5: Plots showing relationship between mean NDVI (a) and ESD values (b) and site counts.

Figure 6: Kernel density plots of NDVI values for each period. Site counts per period are noted for each.

Figure 7: Kernel density plots of ESD values for each period. Site counts per period are noted for each.

Figure 8: Kernel density plots for all sites showing observed NDVI (a) and ESD values (b) as compared to values predicted based on random point processes.