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Check dam agriculture on the mesa verde cuesta

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ABSTRACT

Prehistoric water management in the northern US Southwest was integral to successful subsistence. On the Mesa Verde cuesta in southwestern Colorado, several types of water management features have been identified in the archaeological record, but research into these features has typically focused on the efficacy of reservoirs—a large-scale, labor-intensive, and community-oriented means of collecting and storing water. This focus on large-scale water management features has largely ignored the productive potential of small-scale and low-cost strategies for water management executed by individual households. There is considerable evidence, for example, that extensive check dam networks were constructed and used on the Mesa Verde cuesta, but their actual utility as a small-scale risk-aversion strategy to resource stress has not systematically been explored. This paper identifies all ephemeral drainages on the Mesa Verde cuesta where check dam construction was possible, then applies a maize growing niche model to estimate total yields from check dam farming plots for each year from AD 890–1285. A demographic reconstruction is then used to estimate the percentage of the total cuesta population that could have been supported using only check dam maize yields through time. Results suggest that check dam farming could have supplied a reliable source of surplus annual maize sufficient for household storage needs even during the most populous time periods across the cuesta landscape.

1. Introduction

The Mesa Verde cuesta in southwestern Colorado, the physiographic feature that includes Mesa Verde National Park (Fig. 1), was the most densely occupied area in the northern San Juan region from AD 600–1285 (Glowacki, 2015; Schwindt et al., 2016). Despite an established history of occupation, people began to emigrate en masse from the area in the 1200 s and the region was completely depopulated by AD 1300 (Schwindt et al., 2016; Varien, 2010). Reasons for depopulation were multi-faceted, but compounding social instability (Cameron, 2010) and significant periods of drought (Benson and Berry, 2009) ultimately resulted in a period of social transformation and relocation at a regional scale (Hegmon and Peeples, 2018; Spielmann et al., 2016).

Environmentally-based explanations for population emigration are powerful because changes in the paleoenvironment, including periods of severe drought, can be measured independently from changes in cultural material (Benson, 2011a; Bocinsky and Kohler, 2014; Dean and Van West, 2002; Kohler, 2012; Van West, 1994; Van West and Dean, 2000). Examining changes in the archaeological record through changes in the environment is especially effective on the Mesa Verde cuesta—a high-desert setting with no permanent water sources except for an occasional natural spring and the peripheral Mancos River to the south. The lack of permanent freshwater sources meant successful agricultural production was highly dependent on the cuesta receiving sufficient rainfall throughout the year to irrigate maize and other crops (Benson, 2011a; Bocinsky and Kohler, 2014; Decker and Tieszen, 1989; Minnis, 1989; Rohn, 1977; Scott, 1979; Stahle et al., 2017; Stiger, 1979). Environmental reconstructions, therefore, provide a powerful perspective through which we can interpret past human behavior. Changes in material culture that align with periods of environmental volatility suggest quick, inexpensive, and highly specific responses by a population to mitigate an immediate threat of potential food insecurity. Successful and repeated risk-aversion strategies are eventually established within the specific spatial, technological, and social contexts of the affected population (Braun and Plog, 1982; Fuentes, 2015; Halstead and O'Shea, 1989). This process creates a reactive modification that impacts the local ecological niche (Fuentes, 2016) with the intent to decrease potential food insecurity during future periods of similar volatility. The results of this paper highlight the positive impact the average household could have had on annual food production by constructing a localized ecological niche—which actively decreases the potential for future periods of food insecurity and resource stress despite an unpredictable and potentially volatile environment.

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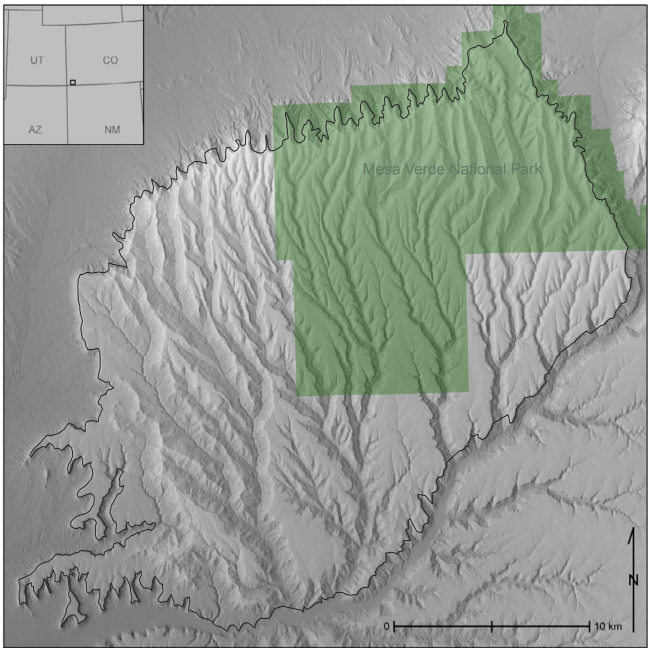

Fig. 1. The Mesa Verde cuesta (outlined in black) and Mesa Verde National Park (shaded in green), located in southwestern Colorado.

1.1. Prehistoric water management features

Evidence for ecological niche construction on the Mesa Verde cuesta is expressed in the archaeological record with the production and use of prehistoric water management features. These features typically include reservoirs, irrigation channels, check dams, and water collection basins (Wilshusen et al., 1997). Although each of these water management features are functionally similar—each is used to collect and/or channel rainwater and snow melt (Crown, 1987)—their construction and use are implemented at different scales of social organization (Wilshusen et al., 1997). Recent research has mostly focused on the efficacy of reservoir features on the Mesa Verde cuesta (Benson et al., 2014; Wright, 2006, 2003, 2000). The initial construction of reservoir features, however, would have required organized cooperative labor from a community of households—if not multiple communities of households.

The production and use of reservoirs on the Mesa Verde cuesta is an example of a group-level response to potential environmental volatility by constructing a local ecological niche that secures access to drinking water and irrigation for surrounding agricultural fields (Bryan, 1929; Crown, 1987; Stewart, 1940; Wilshusen et al., 1997), functioning as a type of cooperative storage and water management for multiple households (Angourakis et al., 2014; Ore and Bruins, 2012). Focusing on reservoirs as a main risk-aversion strategy to environmental volatility, however, assumes these water management features were physically accessible to all households across the cuesta, and ignores the likelihood that individual households were also implementing their own localized risk-aversion strategies—a common practice of households located within arid environments (Ashkenazi et al., 2012; Beckers et al., 2013; Bruins, 2012; Hunt and Gilbertson, 1998). By focusing on community and supra-community responses to environmental pressures and resource stress, we are under-estimating the production of hyper-local ecological niches that could increase the amount of arable land across the cuesta for individual household use.

Individual households—"the minimal social units that form the building blocks for higher-order social groups" (Lightfoot, 1994: 12)—constructed check dam networks in existing ephemeral drainages that would naturally channel water and eventually produce nutrient-rich arable land for agricultural production (Van West and Dean, 2000). Check dams are typically "groups or series of low alignments of unshaped rocks constructed across the bottoms of ephemeral stream channels" that "formed terraces of rich loose silt ideal for farming" (Rohn, 1963: 442) behind and upstream of each check dam feature (Doolittle, 1985; Forde, 1931; Hack, 1942; Homburg and Sandor, 2011). Once the wall alignments were in place across ephemeral drainages, subsequent rainstorms and water runoff would naturally produce a level bed with 5–30 cm of nutrient-rich soil that could be used as small agricultural plots (Homburg and Sandor, 2011). In this way, check dams differ in definition from traditional terracing as they are constructed exclusively within existing drainages, rather than along hillside contours (Rohn, 1963), and rely on rainwater runoff to eventually create level agricultural plots. With little initial labor investment and low-cost regular maintenance, these small agricultural plots would have provided a multitude of advantages for crop production. Check dam networks would have: stabilized the local landscape; been unlikely to fail from water erosion or runoff while collecting nutrient-rich soils; produced a deeper A soil horizon with increased water capacity and lower evapotranspiration (Gillreath-Brown et al., 2019); and naturally replenished soil nutrients within each plot through regular water runoff (Homburg and Sandor, 2011: Table 3). Each of these small agricultural plots would have provided an ecological niche constructed exlusively for cultivating a combination of maize, beans, squash, and potatoes (Cordell et al., 2007; Decker and Tieszen, 1989; Kaplan, 1965, 1956; Kinder et al., 2017)

Check dam networks recorded across the Mesa Verde cuesta (Glowacki, 2012; Glowacki et al., 2017; Hayes, 1964; Nordenskiöld, 1893; Rohn, 1977, 1963; Smith, 1987; Stewart, 1940) are difficult to directly date, but are typically associated with sites from the Pueblo II and Pueblo III periods (AD 890–1285). The likely initial appearance of check dams around AD 890 coincides with a "noteworthy" (Varien et al., 2007: 280) period of low potential maize production in the late 800 s and early 900 s. The correlation between poor environmental conditions and the adoption of a quick, inexpensive, expedient, and highly specific response to a decrease in maize productivity suggests check dam networks were initially a reactive modification to manipulate the local ecological niche. The earliest check dams may have even used brush barriers or other organic materials as an even more expedient and less-costly means of damming ephemeral drainages (Bryan, 1929). The continued construction and use of check dam networks through AD 1285 suggests they were an initially successful risk-aversion strategy that eventually became an established agricultural practice on the Mesa Verde cuesta (Braun and Plog, 1982; Cordell et al., 2007; Haase, 1985; Van West and Dean, 2000). Despite being recognized as a widespread risk-aversion strategy to environmental volatility, the actual intensity of check dam construction and use across the Mesa Verde cuesta remains unclear. This uncertainty is a by-product of the realities of archaeological survey where check dams were inconsistently recorded, recorded as features of neighboring sites (i.e. Hayes, 1964: Table 10), obscured by modern landcover, or destroyed sometime over the past millennia. The following analysis uses a combination of known check dam networks, modeled check dam networks, and the maize growing niche developed by Bocinsky and Kohler (2014) to estimate the efficacy of these constructed ecological niches from AD 890 through 1285 on the Mesa Verde cuesta.

1.2. Paleoclimate modeling and the maize growing niche

Paleoclimate reconstructions use environmental proxies to estimate the ecological conditions of past environments, and in the northern US Southwest, tree-ring widths and regression models of historically-recorded temperature data is used to estimate annual precipitation and temperature in the archaeological past (Bocinsky and Kohler, 2014; Bocinsky et al., 2016). Stahle et al. (2017) have noted that "cool-season moisture conditions currently dominate the paleoclimate component of […] maize niche reconstructions for the region" (2017: 6) because they rely on tree-ring chronologies sensitive to soil moisture variation during the winter-spring months rather than precipitation during the summer growing season. However, the paleoclimate reconstruction presented by Stahle et al. (2017) separating early-warm and cool-season precipitation shows that cool season droughts typically continued into the subsequent warm season, suggesting our current models generally reflect overarching annual precipitation patterns. The model provided by Bocinsky and Kohler (2014), specifically, allows us to combine the two most important variables in successful maize production—annual precipitation and Growing Degree Days (GDDs)—spatially across the Mesa Verde cuesta to predict the annual maize growing niche.

Maize is a highly malleable domesticate that can be successfully grown in a range of environmental contexts (Altieri, 2002; Blake, 2006; Huckell, 2009; Matson, 1991; Merrill et al., 2009), but typical lower thresholds for maize productivity in the US Southwest require 30 cm of precipitation and 1,800 Fahrenheit GDDs (Adams et al., 2006; Benson, 2011b; Bocinsky and Kohler, 2014). Modeling maize productivity is especially useful in the Mesa Verde region to understand the impact of environmental changes on a population. Previous studies in the US Southwest have shown that, while exact consumption levels changed through time (Minnis, 1989), an average 70% of an individual's annual caloric intake was from maize-based foods (Bocinsky and Kohler, 2014; Bocinsky and Varien, 2017; Matson, 2016; Sherman, 2014). The prevalence of maize in the prehistoric diet means years of poor maize productivity would have had a significant impact on the average household's ability to produce enough food to support themselves. By constructing check dam networks, households would have increased their overall potential maize yield on an annual basis by increasing the available amount of arable and naturally irrigated land. Check dam networks are, therefore, a reactive modification to minimize potential food insecurity that produced a favorable ecological niche for maize productivity.

2. Methods

Check dam efficacy is measured by identifying all ephemeral drainages on the Mesa Verde cuesta, eliminating those with slopes outside the known range of archaeological check dam networks, and then applying the maize growing niche model (Bocinsky and Kohler, 2014) across the remaining networks. This process first identifies all potential check dam networks that could have successfully been developed in the archaeological past and then predicts the annual maize yield solely from check dam agricultural plots.

2.1. Potential check dam placement

Each potential check dam network must satisfy two fundamental requirements: 1) check dams must be placed in drainages that channel water; and 2) the slope of those drainages must not be too gradual nor too steep. A Digital Elevation Model (DEM) of the Mesa Verde cuesta (Fig. 2a) is used to model potential check dams by finding areas that satisfy both general requirements for effective check dam networks. Ephemeral drainages that would realistically channel rainwater runoff were identified by using the DEM to model a stream network (via Bivand, 2019: "r.stream.extract"). This process reveals all drainages on the cuesta that would realistically channel water (Fig. 2b).

Archaeological check dams identified on the Mesa Verde cuesta are located in ephemeral drainages with slopes ranging from 2.29 to 28.81 degrees (Hayes, 1964; Rohn, 1977, 1963; Stewart, 1940; Stewart and Donnelly, 1943). Presumably, drainages with slopes below 2.29 degrees would not produce enough water runoff to effectively irrigate a check dam network, and those above 28.81 degrees would produce water runoff too powerful for the check dams to withstand. These two values, however, represent the extremes of slopes for recorded check dam networks. To more conservatively predict potential check dam networks, only drainages with slopes within one standard deviation of the mean—from 4.16 to 18.98 degrees—were used for this analysis. We can assume drainages that have a slope outside of this range would typically not result in an effective check dam network, and therefore are removed from the potential areas for check dam placement. Drainages outside the acceptable range are removed from the analysis by calculating the slope of every cell in the DEM on the Mesa Verde cuesta (Fig. 2c), extracting each slope value that overlaps with a drainage, and averaging the slope values across each drainage. Those drainages with an average slope outside of 4.16–18.98 degrees are removed. Slope values are averaged across drainages because modified landscapes can quickly degrade without regular maintenance (Scarborough, 2015), which can result in decreased slope angles or deep arroyo cuts (Bryan, 1929; Cassman, 1999; Doolittle, 1985; Ore and Bruins, 2012). By averaging across drainages, the hope is to capture what the slope may have been with regular maintenance from AD 890–1285. Remaining drainages within the slope range would have satisfied both fundamental physical characteristics required for an effective check dam network (Fig. 2d).

2.2. Calculating check dam efficacy

The average archaeological check dam plot on the Mesa Verde cuesta is 6.39 by 7.28 m (Hayes, 1964; Rohn, 1977, 1963; Stewart, 1940; Stewart and Donnelly, 1943). Considering all potential check dam networks identified above, households could have created a maximum of 61.9 km^2 of potentially arable farmland in addition to traditional mesa-top farming plots. However, creating plots of soil does not necessarily mean those plots were productive.

To determine the annual efficacy of all potential check dam networks (Fig. 3a), the maize growing niche (Bocinsky and Kohler, 2014) was calculated for each year from AD 890–1285 to determine how many potential check dams were likely productive each year. This analysis uses the lower growing-season GDD threshold of 1800 degrees Fahrenheit, the number originally used by Bocinsky and Kohler (2014), but increases the lower precipitation threshold from 30 to 35 cm. Benson (2011b) has reported that maize crops historically failed in Colorado when annual rainfall was less than 35 cm (via Leonard, n.d.), so this model is calculating a conservative estimate of annual maize productivity. Fig. 3b shows an example of the maize niche model, with these growing parameters, for year AD 1245—a particularly cool and dry year used to highlight the potential negative impact the growing niche can have on check dam productivity. Areas within the niche (green) are predicted to have had sufficient GDDs and precipitation for the year, and areas outside the niche (red) were insufficient in one or both of those variables. All networks that do not fall within the growing niche (Fig. 3c) are removed from the analysis for that year. The total length of remaining check dam networks (Fig. 3d) is then used to calculate the total number of average-sized check dams that would have fallen within the niche each year.

Calculating productivity of each potential check dam network, however, is only a useful measurement if we can estimate the area of maize yield needed to support each household on the landscape for one year. Benson (2011a) examined the soil nutrients in Morefield Canyon on the Mesa Verde cuesta—which are assumed to be constant across the study area for purposes of this analysis—and determined that the soil in this area could have supported the repeated planting of 2470 bu/km^2 of maize for consecutive years. A bushel (bu) is a standard measurement equal to 25.4 kg. Contemporary varieties of Hopi Blue corn—the Pueblo corn variety for which we have the most experimental yields (Bocinsky and Varien, 2017; Ermigiotti et al., 2018)—have a caloric yield of approximately 3500 cal/kg (Sherman, 2014). This means that one bushel of Hopi Blue corn yields approximately 88,900 cal. The average person required the consumption of 746,590.9 cal/year (Sherman, 2014), and 70% of those calories would have come from maize (Bocinsky and Varien, 2017), equaling 522,613.6 cal from maize per person per year. This is the equivalent to the number of calories in 5.88 bu, or 100%

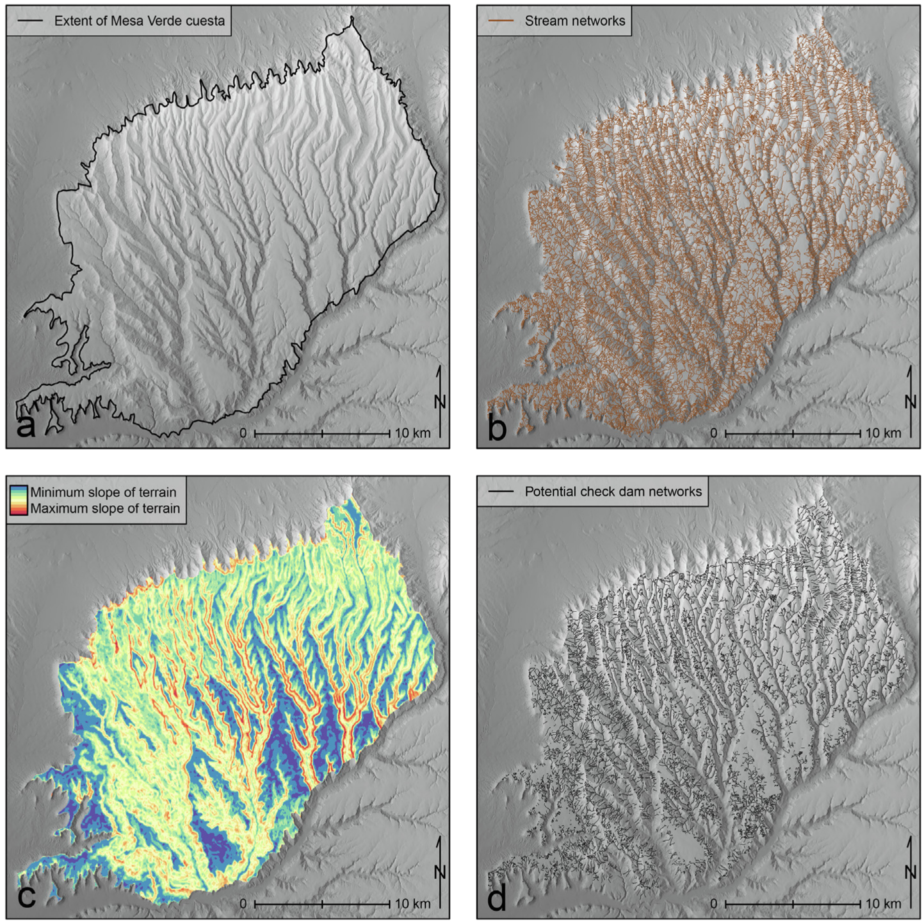

Fig. 2. a) The Mesa Verde cuesta; b) all drainage channel networks (brown); c) slopes of each cell on the Mesa Verde cuesta ranging from the flattest in blue to the steepest in red; d) all drainages that satisfy the physical requirements for a potential check dam network (black).

yield from 0.0024 km^2 of farmland.

Traditionally archaeologists assume that each household represents 5–7 people (Lightfoot, 1994), though this may represent the maximum for any household in its use-life cycle, since simulation suggests that average momentary household size is approximately 3.3 people (Kohler, 2012). By averaging these two estimates to 4.65 people per household per year, each household would have needed the equivalent of 100% maize yield from 0.012 km^2 to satisfy the annual caloric need for household subsistence. The area of one average-sized check dam is 0.000047 km^2 (Hayes, 1964; Rohn, 1977, 1963; Stewart, 1940), meaning each household would require 100% maize yield from approximately 263 check dam plots to satisfy their annual caloric need. The total length of potential check dam networks identified thus far would have provided enough space for 1,331,341 average-sized check dam plots if all potential spaces were developed—which would support up to 5062 households per year given perfect growing conditions. The example shown in Fig. 3d, however, shows that perfect growing conditions cannot be assumed on an annual basis.

The Pueblo Farming Project (Ermigiotti et al., 2018) recorded maize yields from experimental farming fields over ten years. The yields of Hopi Blue corn over the experimental period averaged a yield of 295.2 bu/km^2, or 26,239,502 cal/year (Bocinsky and Varien, 2017). Based on these experimental yields, 0.020 km^2 of maize would need to be planted to realistically expect enough yield at the end of the year to support one person. Using the averaged 4.65 people per household, a realistic yield from 0.093 km^2 of land would support one household for one year. This revised area, informed by the results from the Pueblo Farming Project (Ermigiotti et al., 2018), is more than seven times the necessary area to support each household if we assumed 100% yield per year. This increase means each household would have required a realistic yield from 1991 check dam plots to ensure the production of sufficient caloric yields from maize at the end of each growing season. This larger and more realistic number means that if all potential check dam spaces were developed, a maximum of 669 households per year could have been supported using only maize grown within check dam networks.

2.3. Estimating the Mesa Verde cuesta population

The Village Ecodynamics Project (VEP)—a multi-year, multi-institution project funded by the National Science Foundation (Kohler and Varien, 2012; Kohler et al., 2010)—developed a Bayesian analysis to produce a demographic reconstruction that included the Mesa Verde cuesta from AD 600–1280 (Ortman et al., 2007; Schwindt et al., 2016; Varien et al., 2007). The Bayesian analysis uses tree-ring dates from excavated sites, where they can be paired with detailed ceramic and architectural typologies, to estimate periods of residential site occupation for surveyed sites with representative ceramic and architectural data (for a detailed explanation see Ortman et al., 2007). Based on the proportion of identified ceramic wares and other field observations, the VEP has estimated the probability that each residence was occupied within all time periods for six strata within the VEP II North study area (Schwindt et al., 2016)—including Mesa Verde National Park. This analysis uses the demographic results produced by Schwindt and colleagues (2016), but slightly manipulates the exact VEP time ranges (Varien et al., 2007: Table 3) to fit the study period from AD 890–1285, which represents revised dates for the Pecos periods typically referred to as “Pueblo II” and “Pueblo III” in the Mesa Verde region (Bocinsky

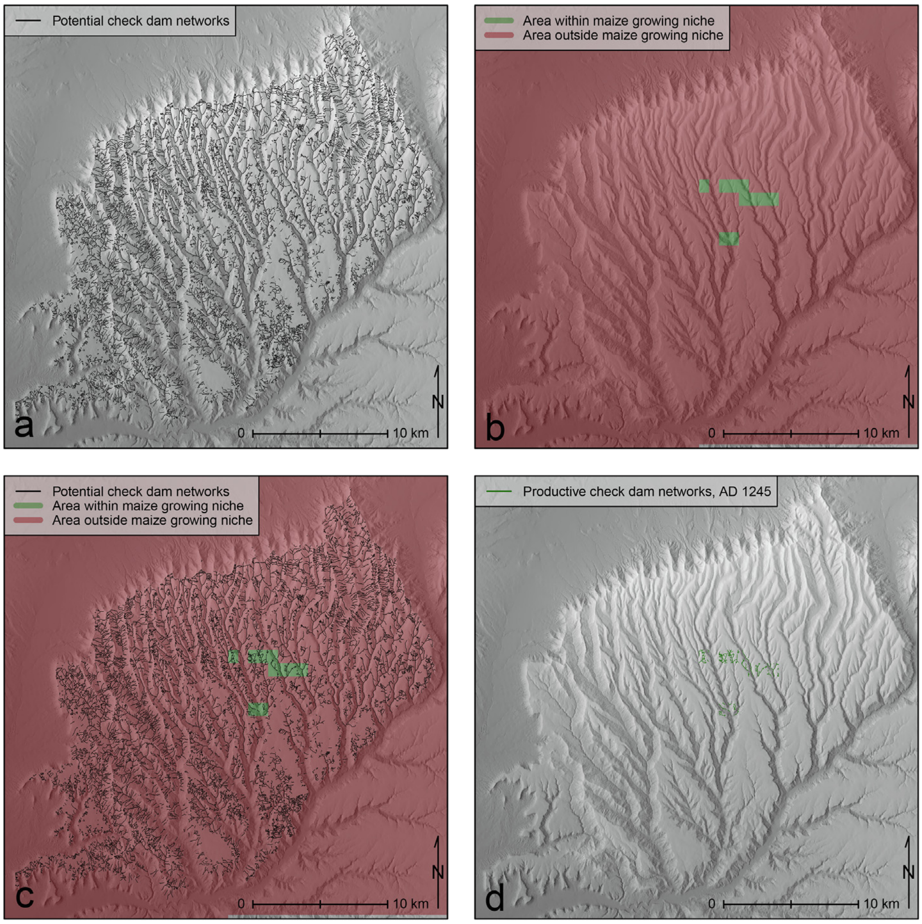

Fig. 3. a) All potential drainages that satisfy the physical requirements for a potential check dam network (black); b) the productive area within the maize growing niche for AD 1245 (green) and unproductive areas (red); c) all potential check dam networks overlaid on the maize growing niche; d) all productive potential check dam networks for AD 1245 (dark green).

et al., 2016).

Table 1 summarizes the modified VEP periods from AD 890–1285 and total number of known residences that are located both on the cuesta and within the Mesa Verde National Park boundary occupied at some point during each associated period. However, the total number of residences does not necessarily represent the contemporaneous household population within each time period prior to AD 1100. In the Mesa Verde region, the use-life of residential architecture prior to AD 1100 is assumed to be shorter than the time periods for which we can assign household occupation (Ortman et al., 2007; Schwindt et al., 2016; Varien et al., 2007). This discrepancy means there are likely more households assigned to each time period prior to AD 1100 than residences occupied at any given time. As residences reached the end of their use-life, people would have constructed new residences, resulting in more residential architecture on the landscape than what would have been contemporaneously occupied. Therefore, the total number of households are "momentized" by dividing the average use-life of residential architecture by the total length of each VEP period, and then multiplying that proportion with the total number of households assigned to the corresponding period (see Varien et al., 2007: 280–282 for more detail). Residential architecture after AD 1100 is estimated to have a use-life spanning the entire length of each corresponding time period, and therefore do not need to be momentized. The results of this calculation are shown in Table 1.

Table 1
The total known and estimated number of households on the Mesa Verde cuesta from AD 890–1285.

Time period (AD)	Total known households	Momentized households	Estimated cuesta households	Estimated total population
890–920	154	69	194	902
920–980	288	86	242	1125
980–1020	620	279	782	3636
1020–1060	578	303	851	3957
1060–1100	801	421	1179	5482
1100–1140	362	362	1015	4720
1140–1180	292	292	819	3808
1180–1225	243	243	681	3167
1225–1260	378	378	1060	4929
1260–1285	430	430	1206	5608

The known number of households in the archaeological record on the Mesa Verde cuesta is also limited to the boundaries of Mesa Verde National Park (Fig. 1). To determine the extent to which productive potential check dam networks could have supported the total Mesa Verde cuesta population at any given time, the estimated number of total cuesta households is calculated by multiplying the momentized number of households by the proportion of the cuesta outside Mesa Verde National Park. Assuming population density was constant across the landscape, this provides an informed estimate of the total household population on the cuesta through time.

3. Results and discussion

Taking the estimated population across the cuesta and the productive potential check dam networks for the same area, the percentage of households supported by check dam agriculture can be estimated for every year from AD 890–1285. Fig. 4 shows the total area of productive farmland within all potential check dam networks (green), and the percent of total estimated cuesta households supported by the maize yield from those check dam networks (blue). A 20-year Gaussian smooth (dark green and dark blue, respectively) is also applied to the

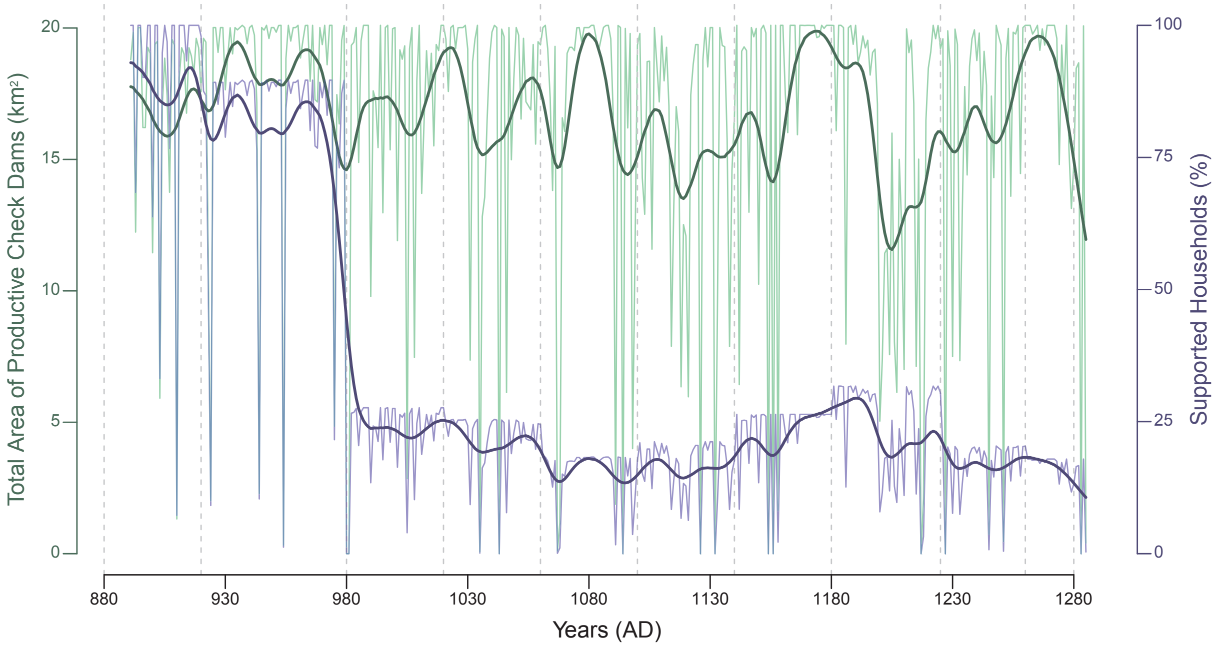

Fig. 4. The total area of potential check dam networks that fall within the annual maize growing niche (light green) and the percentage of households that could be supported using only maize agriculture produced within check dam networks (light blue). The results are also shown in a 20-year Gaussian smooth to better show trends through time (dark green and dark blue, respectively.

results to highlight perceived trends of annual agricultural productivity through time (Jha et al., 2018; Marin, 2010; West et al., 2008).

The results in Fig. 4 show that check dams were relatively productive throughout the entire study period, despite annual variability, providing an average 16.7 km^2 of additional productive land. This amount of additional productive land would have supported an average 34.2% of the cuesta population through time, making these ecological niches a potentially effective strategy against resource stress and food insecurity. The results also suggest that households would have had to change how they used check dam networks through time. The average percent of households supported by check dam agriculture notably decreases at AD 980 (Fig. 4), but this is a result of a dramatically increasing population (Table 1), rather than consistently poor maize yields. From AD 890–980, check dam networks could have provided an average of 83.2% of the total household annual caloric need of all households on the cuesta. After AD 980, the population increase meant that check dams could no longer provide a majority of the annual caloric need from maize, but could still provide an average of 19.8% of each household's annual caloric need. The relatively reliable and high productivity of check dam networks during the AD 800 s and 900 s would have produced at least one century of traditional ecological knowledge—long-term and inter-generational sharing of cultural knowledge concerning ecological systems (Iuga et al., 2017; Savo et al., 2016)—supporting the continued construction, use, and intensification of check dam farming plots even as the population continued to grow in the AD 1000 s through the 1200 s.

3.1. Realistic applications for check dam agriculture

Given these results, we must think about the realistic applications and uses of check dam networks throughout the AD 890–1285 period on the Mesa Verde cuesta. The initial construction and use of check dam networks would have created a dramatic increase in potentially arable land with relatively little labor investment, and the reliable increase in annual productivity would have supported future intensification of check dam development. While check dam networks from AD 890–980 could have provided a significant amount of the annual caloric need for households each year, check dam networks were more likely used throughout the AD 890–1285 period as a low-cost risk-aversion strategy to combat future years of potentially low maize productivity by producing surplus maize for storage.

Household-level storage of surplus maize was common practice in the Mesa Verde region by AD 600, when maize became a significant part of the ancestral Pueblo diet (Spielmann and Aggarwal, 2017). Kintigh and Ingram (2018: 27) highlight ethnographic data from Pueblo farmers suggesting "droughts of up to four years are sufficiently common [and] that an effort is made to maintain two to four years' supply of stored corn." Additionally, Burns (1983) reports (via Parsons, 1936) that historic Hopi households may have stored as much as 60.9% of their annual caloric need from excess food production to maintain their storage needs—although this quantity is *much* greater than the amount needed to maintain 2–4 years' of surplus maize in storage. When maize is stored in unprotected rooms or middens, it is functionally destroyed by insects and rodents after 10 years (Gasser and Adams, 1981). If this spoilage rate is uniformly applied, we can assume that 10% of stored maize becomes unusable every year, eventually becoming non-existent after 10 years. With this spoilage rate in mind, households on the Mesa Verde cuesta needed only store half of the amount reported by Parsons (1936)—about 30.4%—of their annual caloric need from excess food production to regularly maintain 2–4 years' supply of stored maize. Given the ethnographic accounts of maize storage amounts, the proportion of estimated total households occupying the cuesta, and the area of potential check dam networks, check dams could have provided a means of producing surplus foodstuffs for household storage with relatively low investment in construction and maintenance. We can assess the efficacy of check dams as a low-cost, highly-localized risk-aversion strategy to a potentially volatile environment by constructing an ecological niche that facilitates the production of excess maize for annual household storage needs.

3.2. Quantifying "local" ecological niches

To show just how local these ecological niches were through time, a cost-distance estimate was done to quantify the average time households would have needed to travel to maintain neighboring check dam plots for the purpose of excess maize production. As calculated above, each household would require an average maize yield from 1991 average-sized check dam plots to support themselves for one year, and with a goal of storing 2–4 years' worth of excess maize, households could have put as little as 30.4% of their annual caloric need into storage each year. If we assume that maize yield from check dam plots would have provided the excess food needed for annual household storage, then each household would have needed to tend to 606 average-sized check dam plots to produce 30.4% of their annual caloric need for storage purposes. While each household would not have known which check dam networks were going to fall within the maize growing niche each year, they reasonably would have known how much land to cultivate to support their annual storage needs.

The degree of check dam network localization is measured through an iterative process for each known household within a time period. Only known households within Mesa Verde National Park on the Mesa Verde cuesta are used in this portion of the analysis, and potential check dam networks are limited to the same geographic space. For all time periods prior to AD 1100, the process is repeated five times with different sets of randomly selected momentized households in an attempt to best reflect the reality of household occupation on the cuesta. For all periods after AD 1100, the following process is performed only once because all known households were likely occupied for the entire length of each time period. An example of the following process is shown in Fig. 5 for one example household (Fig. 5a) occupied during the AD 1225–1260 period.

- A household location is selected (Fig. 5b);
- The Euclidean distance between the selected household location and all potential check dams is calculated;
- The locations of all potential check dams are sorted from nearest-to-farthest;
- The nearest 606 check dam locations are selected (Fig. 5c);
- The Euclidean distance is calculated from the original household location to the nearest check dam location, then from the nearest check dam location to the second, then from the second to the third, etc. Once the distances have been calculated between all 606 check dams, the distance back to the original household location is calculated (Fig. 5d);
- The round-trip Euclidean distance is determined by adding all distance values calculated in the previous step;
- The distance is converted to on-path travel time and off-path travel time for an estimate of the cost-distance to travel from each household, through the entire check dam network, and back to the household. Tobler's Hiking Function (Tobler, 1993) estimates an average walking pace of 5.04 km/hr for on-path travel and 3.02 km/hr for off-path travel;
- All 606 check dams that were used for a household are then removed for the remaining iterations in a time period, so each check dam plot is counted only once;
- The process is repeated for all remaining households occupied during the given time period;
- The reported travel time range is the average on-path and off-path travel time for all households within a time period.

Fig. 6 shows the range of average round-trip travel time, using on-path and off-path pace estimates, between households and 606 neighboring check dam plots from AD 890–1285 (gray). The annual percentage of total storage needs met for all households is also shown (blue), along with a 20-year Gaussian smooth to highlight trends through time (dark blue). Additionally, vertical lines highlight the years households would have had less than 2 years' supply of stored maize if solely relying on producing 30.4% of their annual caloric need within check dam plots each year (red). The years of maize in storage are calculated based on a constant 30.4% of annual caloric need being put into storage each year, a constant spoilage rate of 10% per year, and does not account for maize being removed for use during years of poor productivity. This display is simply meant to highlight the potential productivity within check dam networks in relation to annual storage needs, and the relative efficacy of check dam networks for producing a reliable food surplus through time. Households would have had at least 2 years of surplus maize in storage for 88.9% of the years from AD 890–1285 by solely relying on maize produced in check dam farming plots. The vertical red lines in Fig. 6 highlight the most environmentally volatile years, resulting in less than 2 years' of stored food. These periods were likely offset by increasing maize production for storage in subsequent years to replenish the total amount of stored foodstuffs (Dean, 2006), and could have fluctuated up to at least 60.9% (Parsons, 1936) depending on the need of a given household. This model also highlights that when households needed to harvest more maize in response to consecutive years of poor productivity, there was ample space for all contemporaneous households to expand farming within unused potential check dam networks to meet that need.

The results show that check dam networks are an example of extremely localized, productive ecological niches. Households would have regularly spent significant time caring for the crops planted in each of these check dam plots, but the travel to and from the totality of those plots would have taken an average estimated range of 94–156 min—-well within the range of regular travel recorded at historic Hopi to maintain agricultural fields (Bryan, 1929). Interestingly, the cost of traveling to check dam networks stays relatively constant from AD 890–1225, suggesting households were living in areas on the cuesta appropriate for extensive check dam networks, even as overall population levels on the cuesta increased and communities became more aggregated through time. The dramatic increase in travel cost to check dam networks at AD 1225 likely reflects changing community settlement patterns (a pattern also noted by Kohler et al., 2020). In the early AD 1200 s, some households began moving into alcove settings, most households began to move towards the center of the cuesta landform where drainage slopes are generally more steep, and households were aggregating into larger villages as population increased throughout the AD 1200 s; each of these factors would have made check dam networks more scarce and farther away from the average household than was the case for the previous 345 years. Furthermore, the increase in travel time to check dams coincides with the most severe period of check dam farming plots failing to provide reliable surplus maize for storage, and perhaps localized risk-aversion strategies shifted at this point to a different strategy. Despite the increase in travel cost to access check dam networks and their decreasing reliability in the early AD 1200 s, they were still likely utilized as most of the extensive networks recorded in the archaeological record—some networks extending up to 60 check dams long in a single drainage (Rohn, 1977, 1963)—are associated with Pueblo III habitation sites on the Mesa Verde cuesta.

4. Conclusions

This analysis has highlighted the substantial productive impact individual households can have on their local ecology, and the resiliency of their local communities. Check dam networks would have provided an effective, local, and low-cost strategy to mitigate the effects of the arid, high-desert, and potentially volatile environment on the Mesa Verde cuesta. The initial increase in maize productivity, and relative reliability of these constructed ecological niches from AD 890–980, would have produced a strong foundation of traditional ecological knowledge in favor of using check dam networks as a household-level risk-aversion strategy to combat potential years of poor productivity. The continued construction and use of check dam networks would have reliably supplemented annual maize yield across the cuesta, providing a means for individual households to actively decrease the potential for food insecurity and resource stress during years of low productivity.

Households would have been able to reliably maintain 2–4 years' of

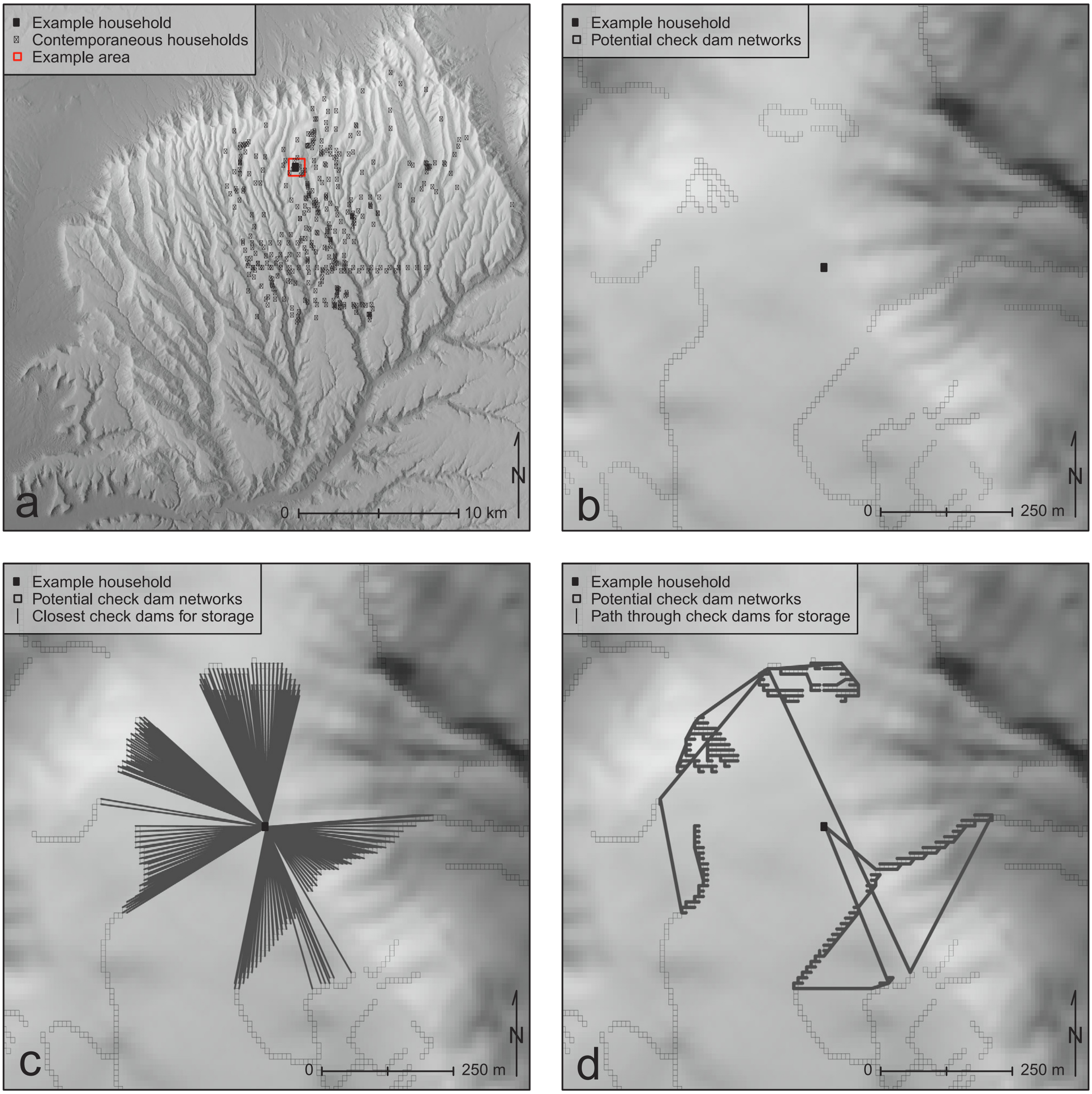

Fig. 5. a) All contemporaneous households from AD 1225–1260 (black), with example household (white), and bounding box for the zoomed-in view (red); b) zoomed-in view of the sample site (white), surrounding household (black), and neighboring potential check dam networks (boxes); c) Euclidean lines from the sample household to the closest 606 potential check dam plots (gray); d) the least-cost roundtrip path (gray) from the example household to all 606 check dam plots and back to the example household.

excess stored maize, by creating nutrient-rich and naturally irrigated farming plots to produce supplemental maize for annual storage needs. Results of this analysis show check dams are an example of an effective, highly-localized, constructed ecological niche that are rarely considered when studying prehistoric water management features. In the northern US Southwest, the introduction and continued use of check dam networks would have made a significant positive impact on annual maize production and subsistence storage practices by reducing the annual potential of food insecurity in this potentially volatile environment.

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CRediT authorship contribution statement

Kelsey M. Reese: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

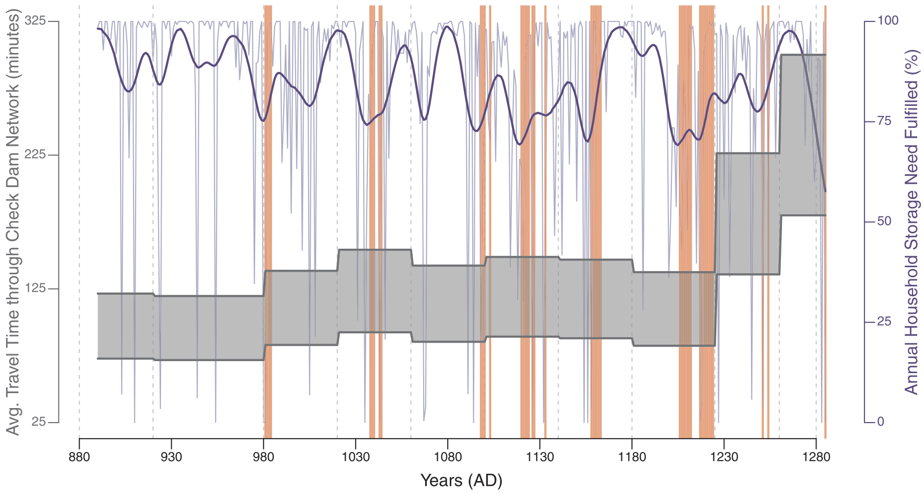

Fig. 6. The range of average on-path and off-path cost, in minutes, of a household to travel through an entire check dam network (gray). The corresponding percentage of annual household storage need produced in those corresponding check dam networks is also shown (light blue) with a 20-year Gaussian smooth (dark blue). Vertical lines represent years where maize in storage is predicted to be less than 2 years (red). The ideal range of maize in storage is based on ethnographic accounts reported by Kintigh and Ingram (2018).

influence the work reported in this paper.

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