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Evidence for the impact of the 8.2-kyBP climate event on Near Eastern early farmers

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The 8.2-thousand years B.P. event is evident in multiple proxy records across the globe, showing generally dry and cold conditions for *ca.* 160 years. Environmental changes around the event are mainly detected using geochemical or palynological analyses of ice cores, lacustrine, marine, and other sediments often distant from human settlements. The Late Neolithic excavated area of the archaeological site of Çatalhöyük East [Team Poznań (TP) area] was occupied for four centuries in the ninth and eighth millennia B.P., thus encompassing the 8.2-thousand years B.P. climatic event. A Bayesian analysis of 56 radiocarbon dates yielded a high-resolution chronological model comprising six building phases, with dates ranging from before 8325–8205 to 7925–7815 calibrated years (cal) B.P. Here, we correlate an onsite paleoclimate record constructed from δ^2H values of lipid biomarkers preserved in pottery vessels recovered from these buildings with changes in architectural, archaeozoological, and consumption records from well-documented archaeological contexts. The overall sequence shows major changes in husbandry and consumption practices at *ca.* 8.2 thousand years B.P., synchronous with variations in the δ^2H values of the animal fat residues. Changes in paleoclimate and archaeological records seem connected with the patterns of atmospheric precipitation during the occupation of the TP area predicted by climate modeling. Our multiproxy approach uses records derived directly from documented archaeological contexts. Through this, we provide compelling evidence for the specific impacts of the 8.2-thousand years B.P. climatic event on the economic and domestic activities of pioneer Neolithic farmers, influencing decisions relating to settlement planning and food procurement strategies.

archaeology | climate | lipid residue analyses | hydrogen isotopes | animal bones

The abrupt climatic event that occurred at *ca.* 8,200 y B.P. in the Early Holocene was triggered by the glacial drainage of freshwater into the North Atlantic and is recorded in multiple climatic archives across the globe (1–3). These paleoclimate signals vary in amplitude, space, and latitude. In the North Atlantic, the Greenland ice cores recorded a negative δ^{18}O excursion starting at *ca.* 8,250 y B.P., which is interpreted as a notable cooling lasting for *ca.* 160 y (4–6). Terrestrial records, such as speleothems, lake pollen, or tree rings in Europe, also registered a climatic change synchronous with the 8.2-kyBP event (1, 2). The evidence for the occurrence of an abrupt climatic event in the Near East at 8.2 kyBP remains scarce (2), although geochemical, isotopic, and pollen records from several lakes in Anatolia (7, 8) registered this change in climate. Some indirect paleoclimatic evidence has suggested that hunter-gatherer societies from the Mediterranean basin and central Europe were deeply affected by the changes in geomorphology and ecology triggered by the 8.2-kyBP event (2) [although other studies suggest the contrary (9)], showing the impact of such an event on well-established hunter-gatherer populations relying on a subsistence strategy in place for at least 100 ky. At around 8.2 kyBP, the Near East was sheltering a pioneer farming population, which had initiated the process of cereal and ungulate domestication *ca.* 2 ky before (10). This sudden climatic crisis thus put to test the farming communities in the Near East and may have accelerated the spread of early farmers out of Anatolia to new pastures in Greek Macedonia, Thessaly, and Bulgaria (11).

Significantly, direct climate proxy records for the 8.2-kyBP event have never been reported from an archaeological site. However, recent advances in the Bayesian analysis of high-precision radiocarbon dates from archaeological stratigraphic sequences have the potential to provide well-dated chronological models against which new paleoclimate records can be built from archaeological materials. One such example is the lipid biomarkers preserved in pottery vessels (12), which have been shown to carry precipitation signals (13), although they have never been used to construct paleoclimatic records. Well-dated onsite paleoclimate records would open the way to exploring human responses, reflected in artifact assemblages, site layout, and architecture, to climatically driven change at settlements and their hinterlands.

We have explored such an approach at the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage site of Çatalhöyük (37°40′01″ N, 32°49′41″ E), which has been extensively excavated since the 1960s. The site comprises Neolithic and Early Chalcolithic settlements spread

Significance

This study reveals that animal fats preserved in pottery vessels from the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage site of Çatalhöyük recorded the abrupt 8.2-thousand years B.P. climatic event in their hydrogen isotopic compositions. In addition, significant changes are observed in the archaeology and faunal assemblage of the site, showing how the early farming community at Çatalhöyük had to adapt to climate change. Significantly, this contribution shows that individual biomolecules preserved in ancient animal fats can be used to reconstruct paleoclimate records and thus, provides a powerful tool for the detection of climatic events at well-dated onsite terrestrial locations (i.e., at the very settlements where human populations lived).

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over 37 ha on the Southern Anatolian Plateau occupied between 9050 and 7150 calibrated years (cal) B.P. (14, 15). Excavations (2001–2008) in the Team Poznań (TP) area of the East Mound exposed a long sequence of vertical stratigraphy, including domestic buildings with floors, walls, and hearths (14); abundant ceramics; stone tools; and human, faunal, and botanical remains. Bayesian modeling of 56 radiocarbon dates (14) revealed six building phases named TP-M to TP-R spanning from *ca*. 8325–8205 cal B.P. (end of TP-M) to 7925–7815 cal B.P. (end of TP-R). The phase TP-O was occupied between 8295–8190 cal B.P. (95% probability) and 8180–8110 cal B.P. [95% probability (Fig. 1*A*); i.e., from the beginnings of the "central event" within the 8.2-kyBP event] (6).

More than 13,000 fragments of pottery were excavated from the TP area, with an increased number of sherds in TP-P. Holemouth vessels dominated the assemblage before the TP-P level, with dense ware groups increasing from the TP-P level, indicating a later intensification of cooking activities. Potsherds (n = 87) from primary contexts from phases TP-M to TP-R were selected and analyzed for organic residues, allowing lipids from foodstuffs processed in the ceramic containers to be characterized (12). The dominant $C_{16:0}$ and $C_{18:0}$ fatty acids indicate the residues are degraded animal fats (16). The low abundance of $C_{18:1}$ fatty acids, the main fatty acid in fresh animal fats, shows that the fats extracted are indeed archaeological. $\Delta^{13}C$ (= $\delta^{13}C_{18:0} - \delta^{13}C_{16:0}$) values range from −3.3 to −0.4‰ (n = 43), of which 41 are consistent with ruminant carcass fats and 2 are very close to being consistent with ruminant carcass fats. The $\Delta^{13}C$ and $\delta^{13}C_{16:0}$ values of archaeological animal fats are stable through time (Mann–Whitney test; P = 0.342 and P = 0.713, respectively), showing that both the origin of fats ($\Delta^{13}C$ values) and the animal's diet (as reflected by the $\delta^{13}C_{16:0}$ values) (17) are similar across all phases (Fig. 2). Thus, the carbon isotopic compositions of animal lipids do not seem to have recorded significant environmental change(s) between 8325 and 7815 cal B.P. However, the hydrogen isotopic composition (δ^2H) of the fatty acids provides a unique opportunity to detect local climatic signals, especially since the ceramic containers in which animal products were processed integrate hundreds of cooking events involving tissues from tens to hundreds of animals. Furthermore, the animals themselves integrate δ^2H signals from both drinking water and diet (18), each animal having consumed tens to hundreds of millions individual plants (19) and experienced hundreds to thousands of drinking events during its lifetime, with carcass fats integrating an all-year round δ^2H signal (13). Crucially, the

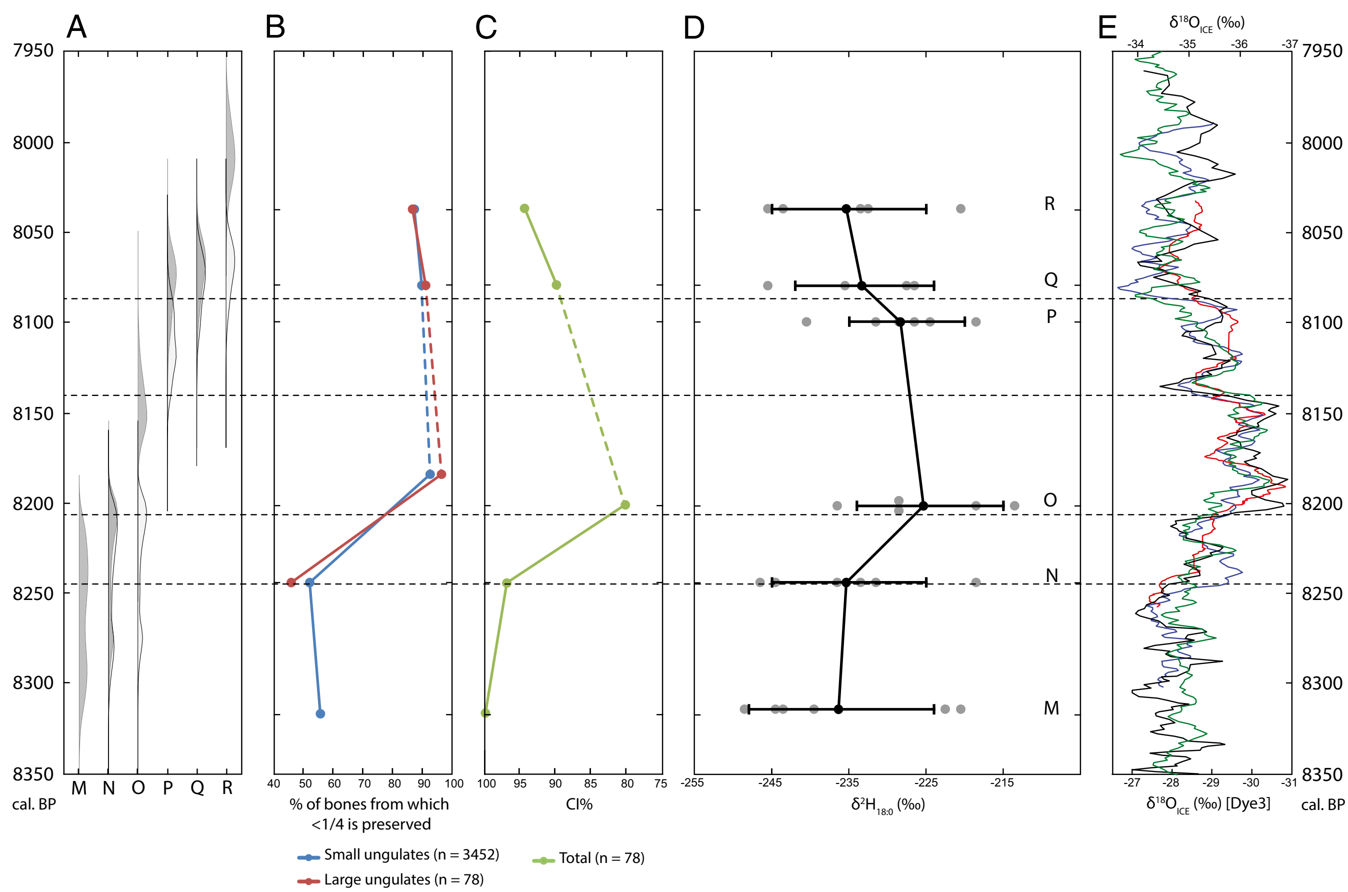

Fig. 1. Archaeozoological and lipid residue evidence for changes in levels M–R of the TP area in Çatalhöyük. TP-P was excluded from the archaeozoological analysis due to the small number of animal remains, which represented only floor deposits. (*A*) Posterior density estimate start (white) and end (gray) dates for the phases M–R (represented by buildings 81, 74, 72, 73, 62, and 61) (14). Note that building 81 is at the bottom of the dated sequence, and thus, only an end date is available for phase M. Durations of the levels (95% probability) are 1–30 y (N), 30–155 y (O), 5–65 y (P), 1–30 y (Q), and 20–110 y (R) (14). (*B*) Percentage of bones from which <1/4 is preserved for small (mainly caprines) and large (mainly cattle) ungulates. (*C*) Completeness index (CI%) of carpals and tarsals for caprine and cattle together. (*D*) δ^2H values for the $C_{16:0}$ fatty acids prepared from animal fat residues extracted from pottery sherds. Each gray data point represents an individual vessel; mean ± 1 SD for each level is in black. Mean SD on measurements (triplicates) is 3‰, ranging from 0 to 10‰. Data in *B*–*D* are arbitrarily plotted in the middle of the posterior density estimates (start/end). (*E*) Water $\delta^{18}O$ values for Greenland ice cores GRIP (red), GISP2 (black), and Dye3 (green). Outer dashed lines indicate onset and termination of the 8.2-kyBP event, and inner dashed lines indicate onset and termination of the central event (6). Adapted from ref. 6, with permission from Elsevier.

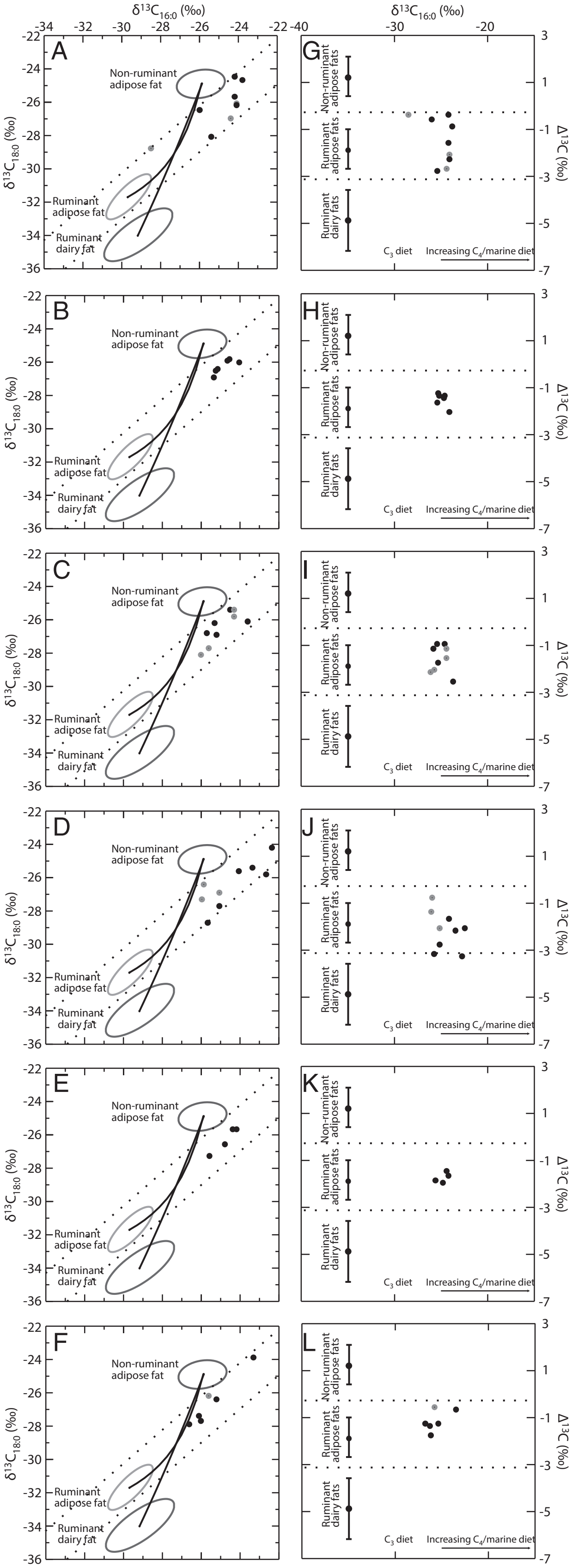

Fig. 2. Fatty acid carbon isotope compositions of lipids extracted from ceramic vessels from Çatalhöyük (TP area). (*A–F*) $\delta^{13}C$ values for the $C_{16:0}$ and $C_{18:0}$ fatty acids prepared from animal fat residues extracted from sherds from Çatalhöyük (TP area) from phases M–R, respectively. The three fields correspond to the $P = 0.684$ confidence ellipses for animals raised on a strict C_3 diet in Britain (20). The analytical error (±0.3‰) is approximately the size of the points on the graph. (*G–L*) $\Delta^{13}C$ values from the same potsherds. Ranges show the mean ± 1 SD for a global database comprising modern reference animal fats from United Kingdom (animals raised on a pure C_3 diet), Africa, Kazakhstan, Switzerland, and the Near East (17). Each data point represents an individual vessel. Samples from which δ^2H values of $C_{16:0}$ and $C_{18:0}$ fatty acids were obtained (Fig. 1*D*) are in black.

isotopic composition of aliphatic hydrogens from fatty acids can be successfully obtained from archaeological animal fats, providing a proxy for the atmospheric precipitation signal (13). The $C_{18:0}$ fatty acid from animal fats was chosen over the $C_{16:0}$ fatty acid due to its metabolic proximity to the main fatty acids from plants ($C_{18:n}$) (20). The δ^2H values of the $C_{18:0}$ fatty acids from the pots from all phases range between –248 and –213‰. Although variable within each phase (SD > 7‰), the $\delta^2H_{18:0}$ values are more enriched by *ca.* 9‰ in TP-O compared with the other phases (TP-M, -N, -P, -Q, and -R; *t* test; *P* value = 0.10) (Fig. 1*D*). This increase in δ^2H values between phases TP-N and TP-O is comparable with the 1–2‰ positive excursion in the same period of carbonate $\delta^{18}O$ values (roughly equivalent to 8–16‰ for δ^2H values) from the Nar Lake, Turkey (8) (160 km away from Çatalhöyük) and the 15‰ positive excursion seen in the δ^2H values of *n*-alkanes extracted from the peat deposit of Tenaghi Philippon in northeastern Greece (21) (*SI Appendix*, Fig. S1).

Our climate modeling studies of the 8.2-kyBP event show a complex pattern of change in the region. An intercomparison of models (22) suggests that the region around Çatalhöyük experienced annually drier (∼4% reduction) conditions but only very weak cooling. However, the magnitude of responses varies significantly depending on the model, estimated strength of freshwater input, and the initial ocean state (23, 24). We, therefore, examined the range of responses from a set of 10 existing model simulations using the isotope-enabled version of the Hadley Centre Climate model, HadCM3, with a variety of inputs and initial conditions (24) (Fig. 3 shows one ensemble member). The simulation predicts modest cooling of 1 °C to 2 °C (Fig. 3*A*) and relatively little seasonal temperature change. By contrast, the change of the precipitation is seasonal; in winter, little change in precipitation over Greece and Turkey is predicted (Fig. 3*B*), but in summer, a widespread decline of 10–15% is expected (Fig. 3*C*). These responses are typical of the majority of ensemble members, which all show cooling over the region, with the majority of models (8 of 10) showing a decrease in summer rainfall. Critically, two models predict a general increase in $\delta^{18}O$ values of ∼1–2‰ of precipitation on average throughout Greece and Turkey, equivalent to 8–16‰ for deuterium, which agrees with δ^2H values recorded directly from animal fats discussed above. These models explain the changes in the $\delta^{18}O$ and δ^2H values that result from an increase in low pressure over Europe, such that air over Greece and Turkey increasingly comes from the eastern Mediterranean (21).

Our dated precipitation record can now be used to explore the impact of the climatic crisis on the activities of the inhabitants of Çatalhöyük. Of particular interest are the ungulate herds, with osteological studies of animal remains showing (*i*) a reduction of cattle herd sizes accompanied by an increase in caprine herd sizes in TP-O and (*ii*) an increase in the degree of bone fragmentation for small and large ungulate grease and marrow-bearing parts from TP-O onward (Fig. 1 *B* and *C*), which is linked to food scarcity/dietary stress (25). An increased number of slice marks associated with each butchering incidence was revealed in TP-O for both cattle and caprines, showing a marked increase in butchering efficiency and meat processing (26). This suggests more extensive utilization of resources and/or increase

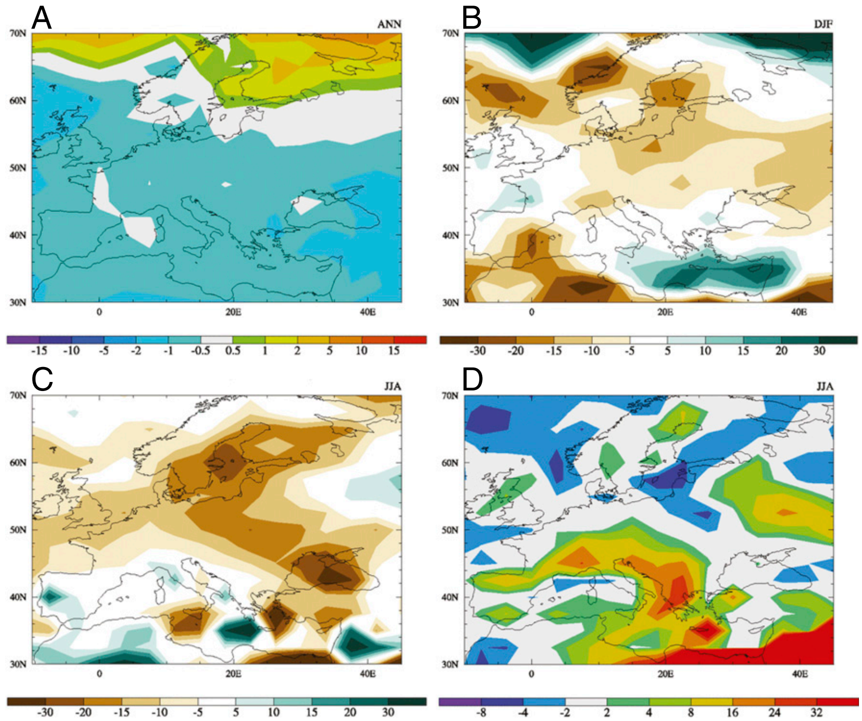

Fig. 3. Modeled 8.2-kyBP climate response. (*A*) Changes in annual (ANN) mean temperature (in degrees Celsius). (*B*) Changes in winter (December, January, February; DJF) precipitation (as percentage change from the control run). *C* is the same as *B* but for summer (June, July, August; JJA) precipitation. (*D*) Summer (JJA) $\delta^{18}O$ values of precipitation (in per mil; ‰). The results are from the ensemble member that shows the response that is most consistent with the isotopic observations (Fig. 1*D*).

in butchering skills in the period of crisis. Skeletal evidence for malnutrition has also been observed in domesticated cattle from this level (27). The consequences of cooler temperatures in winter are an increase in livestock nutritional requirements, with up to twice as many calories needed to maintain normal body temperature and functions, making foddering throughout winter challenging (28), while low summer rainfall could lead to a loss of agricultural productivity (29). Remarkably, human responses are reflected in changes in the site building architecture at this time. Multiroomed large houses with a suite of in-built structures and intramural burials at the bottom of the settlement occupational sequence shift to light shelters with large open spaces in TP-O and TP-P and then, multiroomed dwelling structures with central "living rooms" devoid of major in-built features surrounded by small, cell-like spaces, probably used as storage and working areas (30). These architectural and spatial changes at the site of Çatalhöyük provide evidence for deeper economic and social changes taking place at *ca.* 8.2 kyBP and in subsequent centuries. Smaller, more independent, and more self-sufficient households emerged, replacing the previously dominant communal organization. They proved to be unsustainable and the previously flourishing settlement rapidly shrunk, unavoidably leading to its relatively abrupt and sudden collapse and ultimate abandonment in 7925–7815 cal BC (14).

In summary, the local climate proxy obtained through the δ^2H analyses of fatty acids from animal fats preserved in pottery vessels from the Neolithic site of Çatalhöyük indicates a teleconnection to the North Atlantic abrupt climate event at 8.2 kyBP. Although our local climatic proxy shows only a modest signal for the event, this is entirely consistent with our climate model predications and other isotopic and pollen records from the region. Notwithstanding the apparent weakness of the climate signal, profound human responses are clearly visible in the archaeological record, which perhaps suggest more extreme regional climate impacts than anticipated. Livestock was severely impacted at Çatalhöyük, and the early farming community had to show resilience and adaptability in a period of abrupt climate change.

Finally, the impacts of climate change on human populations are commonly inferred from proxy records obtained remote from archaeological sites. In the Mediterranean, this type of approach has postulated relationships between the 8.2-kyBP event based on ocean, lake, and peat records and broad-scale sociocultural reorganizations (31). Our multiproxy approach, based on climate records derived directly from δ^2H of fatty acids in organic residues in archaeological pottery, links ^{14}C-dated deposits to co-occurring artifacts, ecofacts, and house structures. Through this, we provide evidence for site-specific impacts of the 8.2-kyBP climatic event on the economic and domestic activities of pioneer Neolithic farmers of Çatalhöyük, which clearly influenced their local decisions related to food procurement strategies and settlement planning.

Materials and Methods

Sampling of Potsherds. A total of 87 sherds from the TP area of Çatalhöyük East were selected and sampled for lipid residue analyses. Rimsherds were sampled preferentially as cooking experiments, and analyses of archaeological potsherds have shown that rimsherds contain higher concentrations of lipids than bases and body sherds (32). Potsherds from phases M ($n = 16$), N ($n = 14$), O ($n = 18$), P ($n = 18$), Q ($n = 8$), and R ($n = 13$) were selected for lipid residue analyses. Only sherds from secure contexts (middens and floor deposits) were selected to allow their dates to be established through association with articulated animal bones submitted to radiocarbon dating and Bayesian modeling (14).

Lipid Residue Analyses. Lipid residue analyses and interpretations were based on established protocols (33, 34) (*SI Appendix*, *SI Text*). A subsample (1–3 g) from archaeological potsherds was cleaned with a modeling drill to remove any exogenous lipids (from the soil and handling) and crushed, and an internal standard (*n*-tetratriacontane) and an acidified methanol solution were added. Aliquots of the total lipid extract were derivatized with *N*,*O*-bis (trimethylsilyl)trifluoroacetamide containing 1% trimethylchlorosilane and submitted to analysis by GC and GC/MS to identify the major compounds present; $\delta^{13}C$ analyses of the extracts identified as animal fats ($n = 43$) were carried out using GC/combustion/isotope ratio MS (IRMS) to identify the fats to their animal source (17, 20). Selected ruminant adipose fats ($n = 32$) were then analyzed by GC/thermal conversion/IRMS to determine the δ^2H values of the $C_{16:0}$ and $C_{18:0}$ fatty acids (35).

Archaeozoological Analyses. A total of >220,000 animal bone fragments were excavated in the TP area, of which >100,000 were studied and >6,800 were identified to species. The animal remains were excavated in different contexts: mostly infills of houses and middens but also, floors, clusters, and special deposits. The faunal remains are stored in a depot at Çatalhöyük. Raw data are available online in the Çatalhöyük database (www.catalhoyuk.com/research/database). Level TP-P was excluded from the analysis due to the small number of remains. Specimens were identified to taxon and skeletal element using a reference collection available onsite, and the number of identified specimens (NISP) was determined. The minimum number of elements (MNE) refers to the minimum number of a particular skeletal portion of a taxon. The degree of fragmentation was measured using the NISP:MNE ratio and the completeness index (CI%) using only carpals and tarsals. Specimens that were burnt, digested, heavily gnawed, or weathered were not included in the calculation of CI% to exclude factors altering the completeness of bones.

Climate Modeling. The climate modeling simulations have already been described (24), and we only give a brief description of the key elements here. The simulations used the isotope-enabled version of the Hadley Centre model, HadCM3. The control run uses boundary conditions appropriate to 9 kyBP, and 10 additional model simulations were performed. All simulations assumed that the fresh water input into the North Atlantic from Lake Agassiz was 5 Sv over 1 y. Five of these simulations spread this water over the region from 50° to 70° N, whereas a second set spread it even more broadly from 30° to 70° N. Within each set, five different initial conditions were considered. The resulting climate responses for the North Atlantic and western Europe have been described previously (24) and were broadly similar to other model simulations of this event (22).

In this paper, we have focused on changes in the Middle East and sought to identify the likely robustness of our results across the 10-member ensemble. Conventionally, with modeling studies, the ensemble mean is often presented (24). However, the average does not represent what actually happens and is purely a statistical construct. We, therefore, analyzed all of the ensemble members and identified the range of the results. All models showed a cooling over the region with relatively little seasonality. Similarly, the majority of models showed a summer drying and should be viewed as a robust result from the modeling. However, relatively few of the ensemble members showed an increase in the isotopic ratios. It was related to changes in atmospheric circulation, which were not robust and have a high degree of natural variability. Therefore, this aspect of our simulations should not be viewed as conclusive but does show that atmospheric circulation changes are a vital aspect of the far-field response changes in the North Atlantic.

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