Synchronization of energy consumption by human societies throughout the Holocene

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We conduct a global comparison of the consumption of energy by human populations throughout the Holocene and statistically quantify coincident changes in the consumption of energy over space and time—an ecological phenomenon known as synchrony. When populations synchronize, adverse changes in ecosystems and social systems may cascade from society to society. Thus, to develop policies that favor the sustained use of resources, we must understand the processes that cause the synchrony of human populations. To date, it is not clear whether human societies display long-term synchrony or, if they do, the potential causes. Our analysis begins to fill this knowledge gap by quantifying the long-term synchrony of human societies, and we hypothesize that the synchrony of human populations results from (*i*) the creation of social ties that couple populations over smaller scales and (*ii*) much larger scale, globally convergent trajectories of cultural evolution toward more energy-consuming political economies with higher carrying capacities. Our results suggest that the process of globalization is a natural consequence of evolutionary trajectories that increase the carrying capacities of human societies.

sustainability | radiocarbon | globalization | synchrony | human ecology

Among many species, changes in the attributes of populations coincide over space and time—a phenomenon known as synchrony (1). To date, it is not clear whether human societies display synchronous changes in population attributes or, if they do, what mechanisms might cause synchrony at different scales of space and time. To help fill this knowledge gap, we conduct a global comparison of historical and radiocarbon records over the last 130 and 10,000 y, respectively. These records provide an opportunity to study the long-term synchrony of human energy consumption (e.g., refs. 2–5). The consumption of energy refers to the conversion of biomass into work and waste. In any human population, some proportion of the energy consumed over time goes to meeting the subsistence needs of a population and building infrastructure related to the political-economic activity underlying social organization. Larger populations or greater political-economic activity require more energy during any given time period. Thus, energy consumption provides a metric of the expansion and contraction of human systems.

Investigating the long-term causes of synchrony among human populations complements more traditional studies in sustainability that focus on the potential for a single human population to overshoot the carrying capacity of an environment and collapse or on social institutions that lessen the impacts of large populations on ecosystems (e.g., refs. 6–11). Among synchronous populations, the potential exists for adverse changes in ecosystems and social systems to cascade from society to society, leading to widespread social disruption. Hence, policies designed to promote the sustainable use of resources may benefit from understanding the processes that cause the synchrony of human populations over the long term. In the end, we document significant, long-term synchrony among human systems. The causes of this synchrony may include the creation of trade and migration flows via more local-scale social networks and much longer term, globally convergent trajectories of cultural evolution toward political economies that consume more energy and raise the carrying capacities of human societies. Our study illustrates the enormous potential for radiocarbon records to serve as the basis for millennial-scale, global comparisons of human energy dynamics unprecedented for most other species and raises critical methodological challenges for achieving this potential.

To investigate the synchronous consumption of energy by human populations over the long term, we use two datasets. First, the radiocarbon records of the western United States, British Isles, Australia, and Northern Chile aggregate thousands of radiocarbon ages on preserved organic items from the trash deposits of past human societies, such as wood, charcoal, small seeds, and animal bones. These data provide estimates of changes in the production of waste by populations over time due to the consumption of energy and may be used to infer changes

Significance

We report coincident changes in the consumption of energy by human populations over the last 10,000 y—synchrony—and document patterns consistent with the contemporary process of globalization operating in the past. Our results suggest that the process of globalization may display great antiquity among our species, and this knowledge provides an entry point for integrating insights from archaeological research into discussions on the long-term consequences of globalization for building sustainable societies. Our results demonstrate the potential for archaeological radiocarbon records to serve as a basis for millennial-scale comparisons of human energy dynamics and provide a baseline for further cross-cultural research on the long-term growth and decline trajectories of human societies.

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Data deposition: All data, scripts, and instructions for running our analysis have been deposited on Github (https://github.com/people3k/pop-solar-sync; doi: 10.5281/zenodo.1340714).

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in energy consumption more broadly (12, 13); see also refs. 3 and 14–16. Second, we use energy-consumption records since 1880 from Canada, England and Wales, France, Germany, Italy, The Netherlands, Portugal, and Sweden (4). The radiocarbon records provide estimates of energy consumption over the last 10,000 y in diverse societies. The historical records document annual changes in energy consumption among a set of societies undergoing exponential-like growth due to changes in technology and social organization and were integrated via political alliances, conflict, migration, and trade networks (4). In short, the historical dataset provides a frame of reference (sensu ref. 17) for inferring synchrony in the radiocarbon records.

The synchrony of energy consumption among human societies, at a global scale, could result from two global mechanisms. First, human societies may all respond similarly to fluctuations in an external driver—the so-called Moran effect (18). A longstanding argument in economics is that economic development is controlled, in organic economies, by the availability of energy (4, 19, 20). An organic economy is one in which real-time flows of solar energy into ecosystems limit growth, as opposed to economies that rely more on stored sources of solar energy (fossil fuels). In an organic economy, holding technology constant, biomass produced from fixed areas of land fund population and economic growth, and the amount of solar energy reaching the earth partly sets the limit on the biomass produced from these sources of land. Eventually, populations' subsistence needs must compete for the land needed to produce the biomass that fuels the growth of political-economic infrastructure, which sets limits on growth (4, 20). Thus, we might expect that fluxes in solar energy cause human populations to synchronize, and, if so, human populations in different biophysical environments should synchronize with each other and with the influx of solar energy. Similarly, we should also expect higher synchrony between energy consumption and solar energy in the organic economies documented by the archaeological records than among societies from western Europe more dependent upon fossil fuels over the last 130 y.

Second, direct interactions such as trade and migration, as well as indirect interactions (e.g., common disease vectors or indirect trade), may cause the synchrony of energy consumption among human populations. These mechanisms capture the process of globalization. Globalization occurs when populations become linked through increasingly dense networks, causing the dynamics of systems in distinct locations to couple (21, 22). In such coupled systems, changes in one location may cascade to other locales, leading to instances of widespread social change (e.g., ref. 23). If connections between populations synchronize the consumption of energy by human populations in different locations, then we expect that synchrony will decline as populations become more distant from each other. This is because the strength of interactions between populations should decline as the distance between populations increases.

Results

We document synchrony in two complementary ways. First, we use the mutual information coefficient to estimate high-frequency synchrony. The mutual information coefficient allows us to document if time series oscillate at the same rhythm around their mean trends (24). Second, we use the Spearman's correlations to observe low-frequency synchrony between the mean trends of the time series that take place over thousands of years in the radiocarbon records and hundreds of years in the historical records.

In brief, we find that (*i*) the archaeological and historical records of energy consumption often oscillate in rhythm with each other, but not with solar energy. And, importantly, high-frequency synchrony, in both the archaeological and historical records of energy consumption, declines with distance; and (*ii*) Spearman's correlations document strong relationships between the mean trends of the radiocarbon and historical records, respectively; however, the mean trend of solar energy only weakly correlates with these prehistoric and historic records of energy consumption.

The Rhythm of Energy Records. Fig. 1 *A–D* illustrates the mean mutual information among radiocarbon records of energy consumption and the percentage of significant pairwise mutual information values across six time scales. The patterns in Fig. 1 suggest that many of the radiocarbon records oscillate at a similar rhythm. For example, in Fig. 1*A*, as the bin size of aggregated radiocarbon ages increases, the mean mutual information of the records declines, until a bin size of 500 y, at which point the mean mutual information increases. Similarly, the percentage of significant sequences remains high across small bins and declines at higher bins. As an initial check on these results, we also ran mutual information analysis on raw, uncalibrated radiocarbon ages, and we found synchrony absent any calibration. More importantly, the patterns of synchrony in the archaeological records are redundant with those in the historical records of energy consumption (see below).

While records of energy consumption display high-frequency synchrony, Fig. 1*E* illustrates little evidence of high-frequency synchrony between the consumption of energy and solar energy. The bars in Fig. 1*E* display the mean mutual information between energy consumption records and solar energy records at different time scales for the archaeological datasets and at an annual time scale for the historical dataset. The numbers above the bars are the percentage of sequences that display a significant mutual information and, in parentheses, the percentage of randomly fluctuating simulated radiocarbon records that display significance. The first thing to note is the extremely low mutual information values between solar energy and the records of energy consumption. Regardless of significance, energy consumption and solar energy records share almost no information (i.e., we cannot use a point on one record to predict the next point on another record). In short, it is likely that the significance of the mutual information values in bins 10, 20, and 30 is driven by calibration (*SI Appendix*, section 2.A). More importantly, the mutual information values from the societies documented in the archaeological records equal the mutual information values from the societies in historical times. Societies dependent on organic sources of energy appear no more synchronous with solar energy than fossil-fuel-based economies.

Finally, Fig. 2 *A* and *B* illustrates that the mutual information values of pairwise cases within the same continent (e.g., Arizona and New Mexico) are higher than energy consumption records from different continents (e.g., Arizona and Australia). A Mann–Whitney *U* test indicates that the mutual information values of archaeological cases from within the same continent come from a different distribution of values than those values created by a comparison of records between continents (W = 4,993; $P = 0.01$). This same pattern replicates in the historical energy consumption records from western Europe and Canada ($W = 13$; $P < 0.01$). In sum, the high-frequency synchrony of energy consumption in both the archaeological and historical datasets declines with distance. These patterns are consistent with the idea that direct and indirect interactions via trade, war, and migration—globalization—cause the synchrony of energy consumption.

The Correlation of Mean Trends. The mean Spearman's rank correlation between all of the radiocarbon time series over 10,000 y is 0.79 and among the historical records is 0.94 over the last 130 y ($P < 0.01$ in both cases). This indicates that the long-term

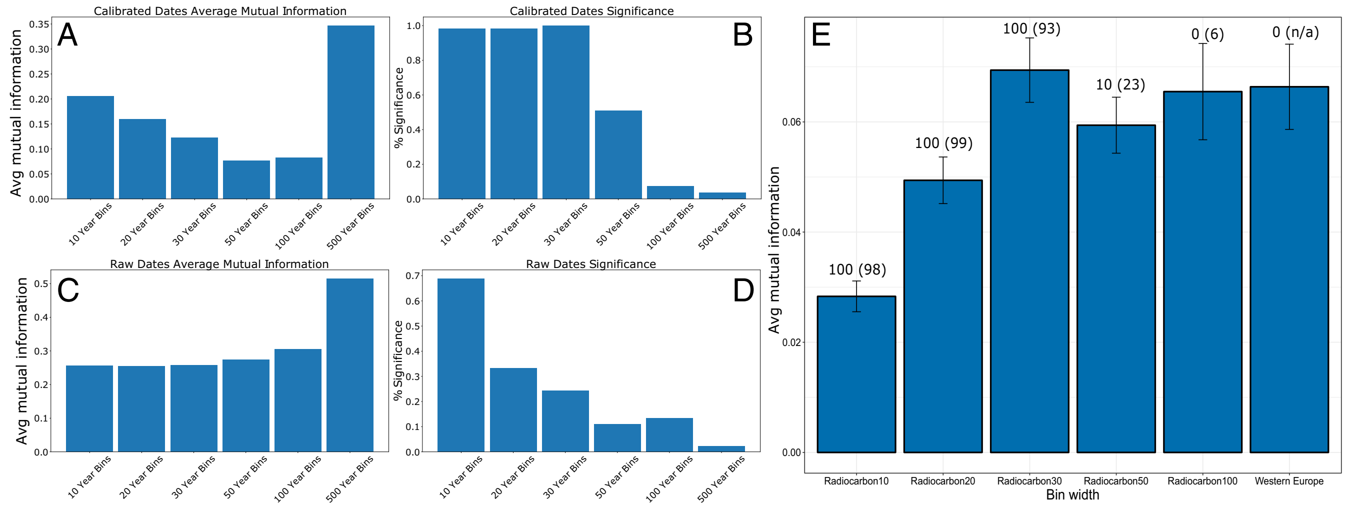

Fig. 1. *A* and *B* display the mean mutual information and percentage of significant pairwise mutual information values for calibrated radiocarbon ages. A mutual information value of zero indicates no shared information; higher values indicate a stronger relationship (more shared information between time series). Significance is calculated by constructing 1,000 null mutual information values for any two time series using a Markov process. If the actual mutual information value is higher than the 95th percentile of the 1,000 null mutual information values, we considered it significant. *C* and *D* display mean mutual information and percentage of significant mutual interactions for "raw radiocarbon ages." Raw radiocarbon ages are ages that have not been transformed to a calendar date. The relationship between radiocarbon ages and calendar ages varies over time, in part, as the amount of solar energy hitting the earth changes the proportion of ^{14}C in the atmosphere (see Data and Methods and *SI Appendix*, section 2 on the confounding effects of calibration). (*E*) The mean mutual information between solar and energy consumption records at different bin widths. Historic western Europe and Canada have an annual resolution. The number above each bar indicates the percent of significant pairwise mutual information values in that bin, and the number in parentheses is the percentage of simulated, randomly fluctuating radiocarbon records, once calibrated, that display significance with solar energy. Avg, average; n/a, not available.

mean trends in energy consumption, within each dataset, display synchrony. The correlation of radiocarbon time series varies by continent, while the correlation of the historical records does not (Fig. 2 *B* and *D*). A Mann–Whitney *U* test indicates that the correlation values between archaeological cases from within the same continent come from a different distribution of values than values created by a comparison of records between continents ($W = 14{,}950$; $P = 0.03$). In contrast, there is insufficient evidence to reject the null in the historical energy consumption records from western Europe and Canada ($W = 87$; $P = 0.43$).

Simply put, while the mean trends of the radiocarbon records all display an exponential increase over 10,000 y, the exact timing of large increases or decreases in the records varies with continent. For example, prehistoric England experiences a large increase with the adoption of agriculture ∼6000 cal BP, while Arizona sees a similar spike coincident with the adoption of agriculture ∼4200 cal BP. It is the same pattern, with different timing, which weakens the correlation of the mean trends. In contrast, in the historical dataset, all of the countries documented, by 1880, were experiencing rapid shifts toward fossil fuels and industrial production. More time depth or diversity of case studies might reveal a similar pattern to that documented in the radiocarbon records due to variations in the initial start of the industrial revolution across countries (e.g., later in Mexico vs. the United Kingdom).

Finally, while the radiocarbon records of energy consumption all correlate with each other, they, again, do not correlate with solar energy or, in a few cases, display a negative correlation (*SI Appendix*, Figs. S8 and S9). In all historical cases, except England and Germany, the relationship between energy consumption and solar energy is not statistically different from random. The lack of relationship between solar energy and energy consumption, or even a negative relationship, among records from organic economies is inconsistent with the expectation that solar energy limits the growth of human systems.

Discussion

In this work, we document that the consumption of energy by human populations displays synchrony in archaeological and historical records. Diverse taxa, including tropical primates, often demonstrate population synchrony (1, 25). Consequently, it makes sense that human populations display some degree of synchrony as well. However, to date, researchers have not attempted to document the synchrony of human populations, let alone at a global scale. Our work fills this knowledge gap by beginning to document the scales of space and time at which human populations display synchrony in their consumption of energy.

Based on our results, we suggest a working hypothesis to serve as a springboard for future research. We propose that the primary causes of synchrony among human societies include the creation of trade, migration, and conflict networks at smaller scales (1–100 y) and convergent trajectories of cultural evolution toward more energy-intensive political economies at larger scales (hundreds to thousands of years). Two of our results, in particular, provide a basis for this proposition.

First, energy consumption records fluctuate, on average, less in rhythm between continents as opposed to records from the same continent (Fig. 2 *A* and *B*). Within-continent variation in high-frequency synchrony corroborates this observation as well (*SI Appendix*, section 2.A.1). For example, a strong pairwise mutual information value in the archaeological dataset comes from the Arizona and New Mexico records. The archaeological records of these states share strong similarities, and the populations were integrated into a pan-American Southwest, Mesoamerican trade network prehistorically (26). The redundant patterns of the archaeological and historical records of energy consumption suggest that the creation of relationships via trade, migration, and conflict, rather than solar energy, cause high-frequency synchrony. This also suggests that the process of globalization is nothing new but, rather, a consequence of social and technological evolutionary trajectories that increase the carrying capacities of human societies.

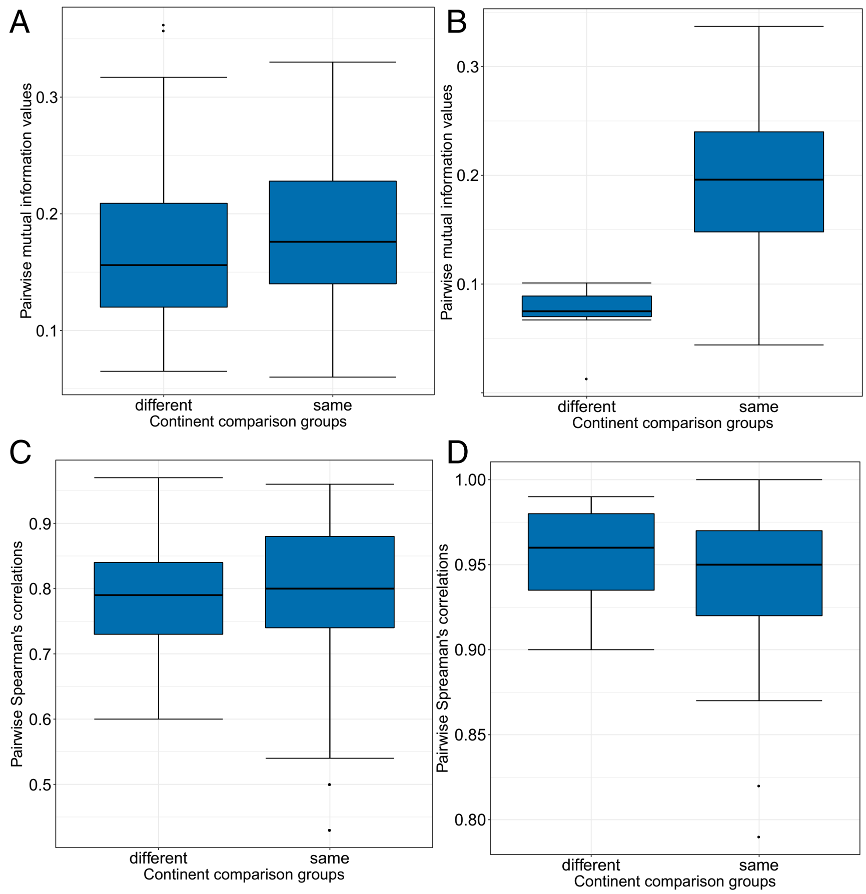

Fig. 2. (*A*) Boxplot of the pairwise mutual information values for 10-, 20-, and 30-y bins combined by continent (different vs. same). (*B*) Boxplot of the pairwise mutual information values among historical sequences. *C* and *D* display boxplots of Spearman's correlations from the archaeological (*C*) and historical (*D*) records of energy consumption.

Please note that we cannot rule out the possibility that external drivers influence the synchrony of human societies at higher frequencies of fluctuation. For example, a consistent outlier in our archaeological data is a significant and high mutual information value between prehistoric southeast England and Colorado. This may occur because of a climate teleconnection that affected these regions throughout much of the Holocene. An important direction for future research remains to investigate the synchrony of local climate records with each other and with records of human energy consumption (radiocarbon records). This will help sort out if more complex teleconnections influence synchrony among human systems over long time spans. Similarly, the process of calibration itself has an effect on the high-frequency synchrony of calibrated radiocarbon records (*SI Appendix*, section 2.A). More work is needed to continue building frames of reference useful for quantifying the relative effects of calibration vs. cultural processes on high-frequency synchrony among radiocarbon records.

Second, in both the archaeological and historical datasets, the mean trends in energy consumption increase over time and, thus, correlate (Fig. 2 *B* and *D*). In fact, most of the trends display exponential-like increases in the consumption of energy over time (*SI Appendix*, section 3). We know that these exponential increases among the historical datasets relate to cultural evolutionary trajectories of increasing energy consumption and higher carrying capacities (4). The convergence of the exponential-like trends in the archaeological datasets suggest that over long time spans, despite diversity in technology and social institutions, human societies converge toward technologies and institutions that allow populations to appropriate ever-larger proportions of the biomass produced by ecosystems, raising their carrying capacity. For instance, energy consumption increases over time in archaeological sequences dominated by hunter-gatherer adaptations in Australia, California, and Wyoming and sequences in which agriculture was adopted, such as Arizona, New Mexico, and the prehistoric British Isles. Two questions about these convergent patterns may be useful for future research.

First, what are the consequences of convergent trajectories of cultural evolution toward more energy-consumptive human systems for understanding the collapse of social–ecological systems? For instance, the continent-wide growth of human systems may lead to more interconnected social–ecological systems at smaller scales of space and time. And this could lead to dynamics captured by the variance reduction-safe-operating-space trade-off hypothesis (VRSOS) (27–29). The VRSOS hypothesis states that, as human agents invest in more technology and social institutions (infrastructure) to reduce variance in their supply of resources over years to decades, social–ecological systems become increasingly complex (specialized and differentiated). As a consequence, the population-climate space in which such systems can maintain their structure shrinks. This means that systems are well suited to a specific range of short-term variation in climate, but unable to cope with changes beyond the past experiences of agents within the system.

Second, why do rates of change vary from sequence–to–sequence in the long-term increase of energy consumption? For instance, Zahid et al. (3) observe similar rates of change in the frequency of dated archaeological remains in parts of North America and Europe between 11,000 and 6,000 y cal BP. This could be the result of similar rates of cultural evolution, albeit divergent in specific forms, toward the same outcome of larger political economies that appropriate more biomass from ecosystems (higher carrying capacities). Another possibility is that rates of change vary systematically with ecological and technological conditions. For example, there is evidence of an optimal biophysical environment for hunter-gatherer population densities (30), and one might expect rates of growth to slow down among environments farther from this optimal than closer to it.

Conclusion

The long-term consequences of human population growth on the health of ecosystems has gained renewed attention (6). At least as important, however, is documenting and explaining the degree of synchrony among human populations embedded within ecosystems over space and time. When populations synchronize, adverse changes in ecosystems and social systems may cascade from society to society. Thus, to develop policies that favor the sustained use of resources, we must understand the processes that cause the synchrony of human populations. In this work, we present evidence that the attributes of human populations, at a global scale, display synchrony for the last 10,000 y. The causes likely include the process of societies becoming more interconnected via trade, migration, and disease flows at smaller scales and common trajectories of cultural evolution toward more complex and energy-consuming political economies at larger scales. Importantly, these causes of synchrony operate at different time scales. This time-scale mismatch may lead to path dependencies that make major reorganizations a common dynamic of human societies.

Data and Methods. To estimate the synchrony of energy consumption among human populations over 10,000 y, we used large samples of radiocarbon ages from states in the western United States (California, Nevada, Utah, Colorado, Arizona, and New Mexico) (31), Australia (32), the British Isles (33), and North Chile (34). We cleaned the datasets to remove (*i*) geological and paleontological dates, (*ii*) dates without radiocarbon lab IDs, (*iii*) dates without errors reported, (*iv*) averaged dates, and (*v*) dates without a site ID or site name. To correct for oversampling biases, we used the binPrep function in the rcarbon package for R (35) to combine different samples from the same site that were within 100 calibrated years of each other. All of the raw dates were calibrated by using the IntCal13 (36) and SHCal13 (37) calibration curves in the rcarbon package (35). We then used the rcarbon package to construct a summed probability distribution of each radiocarbon age time series and binned these probabilities at 10-, 20-, 30-, 50-, 100-, and 500-y bins. We also analyzed the uncalibrated radiocarbon ages in the same bin widths following the same cleaning procedures outlined above. To estimate the amount of solar energy reaching the earth, at a global scale, over the last 10,000 y, we used data on the number of sunspots that occur (38). More sunspots indicate more intense solar activity and more energy reaching the earth and fewer sunspots less energy. We assumed that the more energy that reaches the earth from the sun, the more potential there is for biomass to grow and for humans to consume more energy.

To estimate energy consumption among the eight historical time series from western Europe and Canada, we used data provided by the Joint Center for History and Economics (4). The time series for individual countries attempt to measure the consumption of energy as food, animal fodder, fossil fuels, and electricity. The full methods for accounting and building the time series for each country are published (39–43). For our purposes, these records provide a record of energy consumption independent of the archaeological records, and, more importantly, a sample of human societies that we know were connected via migration, trade, political alliances, and war, as well as all expanding due to social and technological changes increasing the carrying capacity of the societies (the Industrial Revolution). To estimate solar energy reaching the earth at an annual time scale, we used, as above, the annual record of sunspot activity over the last 300 y (44).

To estimate high-frequency synchrony (oscillations at the same rhythm on top of mean trends), we used a symbolic dynamic approach (24). This method required three steps. First, we defined the rhythm of a time series by partitioning the series into a sequence of symbols (known as data discretization). Second, we quantified the mutual rhythms of all pairwise combinations of time series using information theory; and, third, we assessed the statistical significance of the mutual information of time series using a Markov process to resample and construct simulated time series. In this case, we were evaluating the likelihood that a mutual information value would be generated by random resampling of the time series. If the chance was <0.05, we rejected the "null" that an observed mutual information value is due to chance.

In step 1, we preserved the rhythm of the time series by comparing each value of the time series with its neighboring values. Given a time series X, x_{t+1} is transformed in symbols identifying it as a trough point, peak point, increase, decrease, or same (*SI Appendix*, Figs. S10–S22) in the following way: trough point: $x(t+1) < x(t) <= x(t+2)$ or $x(t+1) < x(t+2) <= x(t)$; peak point: $x(t) < x(t+2) <= x(t+1)$ or $x(t+2) < x(t) <= x(t+1)$ or $x(t+2) <= x(t) < x(t+1)$; increase: $x(t) <= x(t+1) < x(t+2)$; decrease: $x(t+2) <= x(t+1) < x(t)$; and same: $x(t) = x(t+1) = x(t+2)$.

The only information contained in the symbolic time series is the rhythm of the initial time series, freeing the time series from changes in amplitude and its mean trend (24). In step two, we calculate the mutual information of any two time series, X_1 and X_2, as

$$I_{X_1,X_2} = H_{X_1} + H_{X_2} - H_{X_1,X_2}, \quad [1]$$

where H_{X_1} and H_{X_2} are the entropy of the symbolic series X_1 and X_2, and H_{X_1,X_2} is their joint entropy (see *SI Appendix* for more details).

Finally, to determine whether observed mutual information values are likely to have occurred by chance, we used the "surrogate type 2" resampling method (24). This method preserves the short-term structure of the untransformed time series. Calculation of mutual information and creation of surrogate time series were conducted in Python and R (45) (scripts available, https://github.com/people3k/pop-solar-sync).

To estimate low-frequency synchrony, we analyzed the mean columnwise Spearman's correlation between the different radiocarbon and historical energy consumption time series using the Synchrony package for R (46, 47). This allowed us to assess the degree of synchrony between the mean, mostly exponential trends of the records. Next, we analyzed the pairwise Spearman's correlation between the archaeological and historical records of energy consumption, as well as between the energy consumption and sunspot records.

Inferring Synchrony from Radiocarbon Records. A major methodological challenge to using radiocarbon records to estimate the synchrony of energy consumption (or population) is the risk of overinterpreting the correspondence of peaks and troughs in time series of calibrated radiocarbon ages (14, 15). The issue is that the calibration process itself, which is the application of well-studied temporal proxy records in an effort to convert ^{14}C time into calendar time (48), may generate some high-frequency synchrony, especially with the record of solar energy, as solar energy affects the proportion of ^{14}C in the atmosphere. Here, we used three methods to assess the effect of calibration on high-frequency synchrony (*SI Appendix*, section 2).

First, we analyzed whether the whole sequence of peaks and troughs were oscillating at the same rhythm. Just as with the "null model" approach developed by others (e.g., ref. 15), we constructed surrogate time series resampled from the real data, which allowed us to assess the chance that a particular mutual information value would be generated by chance. This means that we generated 1,000 pairwise mutual information values from randomly resampled time series and compared the actual mutual information values to the distribution of 1,000 values created by this procedure. Significant values are those greater than the 95th percentile of the distribution of 1,000 values created by resampling.

Second, we created 100 sequences of 1,500 simulated radiocarbon ages by drawing 100 samples from a randomly fluctuating, uniform distribution of 1 million mean radiocarbon ages. We then analyzed the high-frequency synchrony of these simulated sequences summed into bins of 10-, 20-, 30-, 50-, 100-, and 500-y intervals for both calibrated and uncalibrated simulated dates. When analyzing the calibrated ages, we calibrated and constructed summed probability distributions using three different standard errors: 20, 50, and 100. This allowed us to investigate how changes in error affected the synchrony of calibrated radiocarbon ages with each other and with solar energy (*SI Appendix*, section 2.A).

Finally, and, most importantly, we created a frame of reference for what patterns of synchrony should look like among modern human societies by analyzing the synchrony of energy consumption from western Europe and Canada (a frame of reference sensu ref. 17). We know that these societies all experienced increases in energy consumption over the last 130 y and were integrated to various degrees via migration, trade, and war. The two methods above allowed us to begin to quantify how much the process of calibration may affect high-frequency synchrony, but will always leave one with an ambiguous situation in which synchrony may be driven by both calibration (methodological procedure) and processes operating in the past. This is the classic problem of archaeological inference. By analyzing the patterns of synchrony in the historical records, we identified patterns of synchrony between energy consumption records and energy consumption and solar energy to juxtapose with the archaeological data. To the extent that the archaeological patterns of synchrony match those of the modern cases, we can be more confident that the patterns documented in the archaeological records were driven by similar processes as the patterns in the historical records. To the extent that the patterns are not redundant between the two sets of records (archaeological vs. historical), then either (*i*) calibration is obscuring the patterns and driving most of the synchrony, or (*ii*) the dynamics of the archaeological cases were different in some fundamental way from those in the historical record. As noted in *Results*, we saw a strong congruence of patterns between the two datasets, which suggests the operation of similar underlying processes, although more work is needed.

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