PNAS RESEARCH ARTICLE | ANTHROPOLOGY OPEN ACCESS

# Economic inequality is fueled by population scale, land-limited production, and settlement hierarchies across the archaeological record

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Edited by Clark Larsen, The Ohio State University, Columbus, OH; received February 22, 2024; accepted November 4, 2024

**Defining wealth broadly to include wealth in people, relational connections, and material possessions, we examine the prehistory of wealth inequality at the level of the residential units using the consistent proxy of Gini coefficients calculated across areas of contemporaneous residential units. In a sample of >1,100 sites and > 47,000 residential units spanning >10,000 y, persistent wealth inequality typically lags the onset of plant cultivation by more than a millennium. It accompanies landscape modifications and subsistence practices in which land (rather than labor) limits production, and growth of hierarchies of settlement size. Gini coefficients are markedly higher through time in settlements at or near the top of such hierarchies; settlements not enmeshed in these systems remain relatively egalitarian even long after plant and animal domestication. We infer that some households in top-ranked settlements were able to exploit the network effects, agglomeration opportunities, and (eventually) political leverage provided by these hierarchies more effectively than others, likely boosted by efficient intergenerational transmission of material resources after increased sedentism made that more common. Since population growth is associated with increased sedentism, more land-limited production, and the appearance and growth of settlement hierarchies, it is deeply implicated in the postdomestication rise of wealth inequality. Governance practices mediate the degree of wealth inequality, as do technical innovations such as the use of animals for portage, horseback riding, and the development of iron smelting.**

inequality | prehistory | Asia | Europe | Americas

Over the last decade, archaeologists and geographers have greatly sharpened our understanding of how humans have transformed global environments over the Holocene (1, 2). It is no less important to understand how our actions over this period have transformed our societies, especially with respect to how we stand relative to one another. Yet no comprehensive, worldwide, data-based description of levels of economic inequality prior to the development of writing exists [partial exceptions include (3, 4)], although important advances in explaining the rise of social complexity more generally have recently appeared (5). It is important, though, to understand the dynamics of economic inequality on its own before bundling it with measures of social complexity if we are to understand the extent to which it is a precursor to, or a consequence of increasing sociopolitical complexity. Moreover, we find reason to question some accounts of the long-run relationship, in prehistory and preindustrial societies, between economic inequality and average income, which constitutes the "Kuznets relationship" (6). The data presented here suggest that this relationship was not random during these periods, as asserted for example by Milanovic (7), but over long periods a generally positive relationship between economic inequality and economic growth can be discerned in most but not all world regions. [See the SM and (8) for the distinction between wealth, income, and the nature of our proxy.] In this Special Feature, Green et al. (9) discuss evidence for the Kuznets relationship in this database in more detail and Ortman et al. (10) graph this relationship employing Gini coefficients aggregated by region and phase, through calendar years rather than Δyears (defined below). At these more granular temporal and spatial scales this relationship is highly variable.

Our first goal in this paper is to describe the main contours of a database of 1,173 archaeological sites with at least 5 penecontemporaneous measured residential structures each (47,019 structures altogether), distributed throughout the world (see map in ref. 8). Though

## Significance

Growth of wealth differences among households has been a long-term though not universal trend in the Holocene. Marked increases typically lagged plant domestication by 1,000 y or more and were tightly linked to development of hierarchies of settlement size and land-limited production. We infer that the social upscaling (growth of polities in population and area) that typically began one to two millennia after agriculture became locally common, and continued in some areas throughout the Holocene, interfered with traditional leveling mechanisms including enforcement of egalitarian norms. Settlement hierarchies rewired human interaction networks, enabling greater wealth inequalities among households in the highest-ranked settlements. We define "polity-scale effects" to estimate the average effect of development of settlement hierarchies on site-based Gini values.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

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T.A.K. and A.B. are organizers of this special feature.

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This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2400691122/-/DCSupplemental.

Published April 14, 2025.

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obviously incomplete—it is but a small sample of known sites, which is in turn a minuscule sample of those ever occupied—this is still, by far, the largest and most spatially distributed sample ever assembled in service of monitoring degrees of inequality. In this paper, we use the consistent measure of Gini coefficients based on house sizes to estimate wealth differentiation, where wealth is considered to have embodied, relational, and material dimensions (8, 11). This approach allows us to analyze times much earlier than Imperial Rome which until recently was the earliest horizon for inequality studies (12). For reasons presented in ref. 10, our measure of inequality in housing is likely an underestimate of either inequalities in accumulated social capital or wealth; Ortman et al. (10) also argue that the house-size proxy tracks income (a flow) more closely than wealth (a stock). Minimally, these house-size-based Gini indices (which like all such coefficients range from near 0 when residence sizes are nearly the same, to near 1 for highly unequal distributions) represent differential prosperity among households within a settlement. These are termed wealth differences for convenience, without discounting the relevance of income to wealth. We discuss known biases and limitations in this sample in *Materials and Methods*.

Our second goal is to provide a high-level account for the patterns observed in these data. Given the large areas and periods of time covered these explanations must draw on factors potentially visible in many areas, ignoring those particular to one time or region. Past descriptions of inequality through time based on architecture have failed to develop a systematic way of characterizing sites from which the data were drawn. Mixing small hunter-gatherer camps and capitals of empires, however, can blur regional trajectories of inequality. Here, we characterize sites according to their position in the local site-size hierarchy (“WhichLevel” ranging from 1 to 5 in these data) and according to the number of levels in that hierarchy (“NOfLevels,” range 1 to 6). For example, an isolated farming hamlet would be coded as 1 for both WhichLevel and NOfLevels. Below we demonstrate that two variables are consistently among the best predictors of house-size-based Gini variability in our data. The first is Social Advantage (SA), formed by adding WhichLevel to NOfLevels (*SI Appendix*). The resulting index has 10 levels in our data (*SI Appendix*, Fig. S1). The appearance of SA as a key predictor of inequality in the regression analyses discussed below justifies our use of it to describe inequality trends through time. The second is a measure of the extent to which production is limited by land rather than labor. This is measured in the variable Fourscale, which is an index of the degree of land intensification, or efforts to produce more through expansion of suitable land (13) (*SI Appendix*, Figs. S3 and S7 and Table S1). Values of 1 for this variable indicate systems where production was limited only by labor; values of 4 indicate production in highly modified landscapes including such landesque investments as large-scale terracing, irrigation, or drainage works. Under population growth good farming land eventually becomes scarce relative to labor; this variable will increase in value as people use part of the available labor supply to augment the effective supply of land.

Archaeologists have long documented regional sequences in which settlement hierarchies emerge from small undifferentiated settlements as population grows and undergoes economic and political differentiation (14–17). These hierarchies might be thought of as local and temporary equilibria of entropy-maximizing processes governing flows of people, goods, and services under constraints including those affecting site locations and available transport (18), although this definition underplays the potential structuring power of political processes. These properties suggest that both position in a settlement system and the number of levels in that system provide information about system population and degree of political and economic differentiation that may be difficult for archaeologists to otherwise recover from the partial evidence typically available. In effect, even when these hierarchies are loose and imperfect (19) archaeologists can estimate the location of a site in a hierarchy, and the number of levels in that hierarchy, more readily than they can such determinants of that hierarchy as system population, the map of population distribution, and the flows relevant to network structure. As shown in *SI Appendix*, Fig. S2, SA and Polity Population (where that can be estimated) are strongly positively correlated ($pseudo\text{-}r^2 = 0.59$). We define polities as the largest autonomous political community/unit with which the site-centered community ordinarily affiliates. We consider SA to be an ordinal estimate of the minimal size of the connected network of people whose work and interactions create wealth (and inequalities therein). It is a minimal estimate because it does not take into account possible connections with neighboring settlement hierarchies (polities).

We also introduce a characterization of the location of sites within a settlement system that provides a consistent descriptor even as the number of levels in the system (and thus the value for SA) changes. This is done by differentiating between “Basal” and “Apex” sites. Basal sites are those where WhichLevel = 1, regardless of the number of levels in the relevant settlement system. Such sites are thus always at the bottom of any hierarchy, if such a hierarchy exists. Apex sites are those at the top of the focal hierarchy, whatever its size (*SI Appendix*, Derived Variable Definitions). These variables are important because the difference in the average Gini values for Apex and Basal sites is an estimate of the magnitude of the effect that polity size (or SA) has on average Gini values. We define this difference as the Polity-Size Effect.

Finally, throughout this paper we adopt a convention developed by Bocquet-Appel (20) to characterize the Neolithic Demographic Transition (NDT)—a process which, like the growth of inequality, takes place over long periods across vast areas. This makes the absolute date of population expansions (in his usage) less useful for comparing NDTs in different regions than is the timing of those expansions relative to the local arrival of domesticated plants. Just as plant cultivation and increased sedentism initiate the NDT, the population growth and economic differentiation that the NDT accelerates have consequences for the development of inequality. Accordingly, we will use “Δyears” (the difference between the calendar date for the structures at each site, and the date by which agriculture has become locally common) to place sites in time, putting regional trajectories beginning at different absolute dates on this common scale. Several other papers in this SF use the more familiar calendar dates instead, which are more convenient as the areas discussed get smaller, or as the focus turns to recent periods. *SI Appendix*, Fig. S4 presents an alternative description of site-based housing differentials through time using calendar years rather than Δyears.

## Results

### Describing Inequality through Time and across Regions.

***The World sample.*** Fig. 1, *Top* panel, reports Gini coefficients through Δyears for all sites with at least 5 penecontemporaneous measured residential structures. Loess lines (span = 0.9) identify temporal trends. Sites from Africa (n = 14) and Oceania (n = 24) are included in the World panel, and in the regression analyses of the World sample, but are not graphed or analyzed separately due to small sample sizes (see discussion in refs. 21 and 22). *SI Appendix*, Fig. S8 puts the Gini sequences graphed in this section into relationship with median house size calculated by site (*Discussion* and *Conclusions*).

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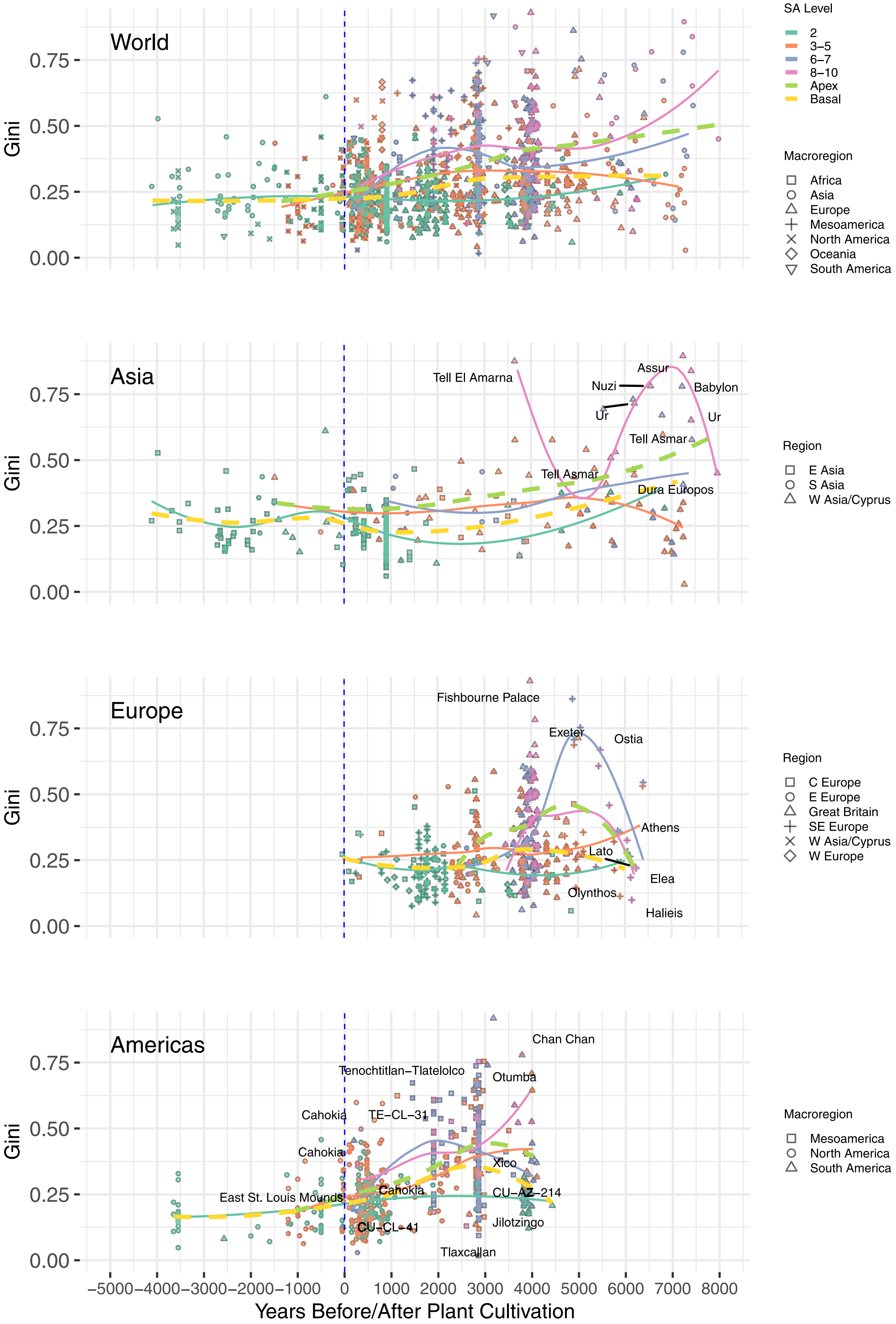

**Fig. 1.** Site Ginis by world area through Δyears, controlling for SA level and designation as Basal or Apex (see text and *Materials and Methods*). Years before/after plant cultivation (Δyears) are structure dates relative to the date when agriculture became locally common. The vertical line marks onset of common local plant cultivation. Seven sites from Asia predating Δ-5000 are not plotted. Only sites in the SA 8-10 category (generally the largest sites) in the macroregional panels are individually labeled. Smoothing is by loess (span = 0.9). Sample sizes as in Fig. 3.

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In the World sample, most sites without agriculture are at SA = 2 (requiring a score of 1 for both WhichLevel and NOfLevels). Though such sites have variable house-size Ginis, the central tendency shown by the loess fit is somewhat below 0.25. It is notable that this same Gini coefficient continues to pertain to SA 2 sites with agriculture. This may reflect social rejection of conspicuous differences in these small-scale settings (23), including operation of gifting economies in which much wealth is given away; another possibility is that little production in excess of subsistence needs (surplus) was generated with early domesticates. On average, across the world and through the time this sample encompasses (8), the degree of house-size differentiation within the smallest-scale settlements was extremely modest regardless of subsistence base or technological repertoire. This provides some empirical support for arguments that find a special place for equality in prehistory and early history (24). SA 2 sites however disappear from our sample ~Δ6500 as they are interrupted or co-opted by larger-scale societies.

A relatively small degree of house-size differentiation does however emerge with the onset of farming (see lines for SA levels > 2, Fig. 1, *Top*). This is accompanied by a simultaneous increase in the Ginis for Basal sites, since this category (unlike the SA = 2 category) includes sites where WhichLevel = 1 but where NOfLevels > 1. Worldwide, even higher levels of site hierarchy (SA > 5) appear with the development of agriculture. The degree of house-size differentiation in these higher-ranked sites is modest at first, but grows steadily in the world sample. Virtually all the increase in Gini coefficients following the onset of farming is within settlements where SA > 2, including those at the Basal level that are enmeshed in multitiered settlement systems.

The relationships among these tiers reveal interesting dynamics that appear to have been little discussed. For example, Gini values for SA levels 3 to 5 begin to decline after ~Δ3500, simultaneous with the increase in Ginis in sites with SA > 5. At this spatial scale, it is always possible that such patterns are due to distinct portions of the world coming into (or leaving) the sample (*SI Appendix*, Fig. S5), yet since this pattern is also evident in some much smaller spatial divisions it may reflect a process in which both the richest and poorest households were attracted to sites at the top of the settlement hierarchy, raising Gini coefficients at these sites while making lower-ranked sites more socially homogeneous. This movement is likely systemically connected (as both cause and effect) to the economic growth in top-ranked sites that much recent research connects to interactions between knowledge, institutions, population, and culture (25) (*Discussion* and *Conclusions*). This aggregate sample also reveals a consistent trend of growth in inequality in the highest-ranked settlements from Δ0 to the end of the sequence; degree of inequality accelerates after ~Δ4500. Of course, the high degree of smoothing in these figures masks considerable regional and temporal variability in inequality such as reported by Ellyson et al. for the pre-Hispanic Pueblos of the US Southwest (26) or Porčić (27) for the Balkans. This same smoothing however emphasizes that the long-term trend has been for residences in sites at the top of settlement hierarchies to become increasingly unequal in size worldwide.

**Asia.** The 265 sites in Asia constitute 23% of the sample, with concentrations in the (Middle) Mumun period of Korea (86 sites) and in the Jomon and Yayoi periods of Japan (60 sites). Trends are similar to those in the worldwide sample, although most sites in the highest SA tier do not appear in the sample until late in the sequence, after ~Δ4500. Among these are the Mesopotamian cities of Babylon, Ur, and Assur, the earliest phases for which we have data are assigned a date of 2350 BC in our database. The decline of Gini coefficients for the SA 8-10 stratum at the end of the sequence is mostly due to the latest of these, Dura Europos in Northern Mesopotamia, with a mean date of ~40 BC/~Δ7980 and the lowest Gini of the group, 0.45. *SI Appendix*, Fig. S8 shows a general long-term trend in Asia from small residential units with low inequality early in time to generally larger residential units and higher inequality later in time. The joint long-term increase in both median house-floor area and disparities in house floor area resembles a Kuznets wave (7)—albeit one that takes place over a very large spatiotemporal frame and potentially within the wealth rather than income domain. Notably it does not follow the sort of random pattern expected for the preindustrial period (7).

**Europe.** The 376 sites in Europe constitute 32% of the sample. Within Europe, sites in Britain (174), mostly of Roman age, and SE Europe (97), mostly Neolithic and Chalcolithic, are especially numerous. Europe's history of inequality (Fig. 1, third panel) is quite different from those for Asia or the Americas, at least within this sample. First, there are almost no preagricultural sites in the Europe sample. Europe's neolithization was mostly by means of migration from SW Asia (28, 29), so its beginnings are truncated relative to Asia and the Americas, where domestication was autochthonous in some regions. Second, and connected to the first point, Apex sites are rare until ~Δ2500 and do not begin to increase in inequality until then. This is most likely because farming settlements were budding off (rather than growing in place) as farming initially spread to the west and north. For some 2,000 y after the arrival of farming in any area this minimized the local growth in population and competing land claims that apparently encouraged site hierarchies to form (13). The loess lines for SA classes 6 to 7 and 8 to 10 are destabilized by the large group of Romano-British sites ~Δ4000; summaries for the Apex and Basal sites are more useful. There is a marked decline of Gini coefficients in sites with SA > 5 after Δ6000. This is (proximately) due to the influence of classical sites like Halieis in the Argolid (with a Gini of 0.10 at 350 BC/Δ6150) and Olynthos in NE Greece (part of which was developed on a Hippodamian grid plan) with a Gini of 0.18 at 374 BC/Δ6126. The overall effect of the lack of prefarming sites and the high levels of inequality present by Δ4000 is for a short (relative to Asia) but dramatic history of increase followed by decline in inequality. *SI Appendix*, Fig. S8 shows that despite these differences with Asia, the relationship between the Gini coefficient and the median house size (the Kuznets relationship) is somewhat similar to that in Asia in its long-term trend from smaller residences with low inequality toward larger residences with greater inequality.

**Americas.** The Americas contribute 484 sites (41%) to the database with concentrations in Central Mexico (110) and Southeastern North America (69). The degree of pre- or nonagricultural social differentiation is slightly lower than in Europe or Asia, though with farming the SA 2 sites rise to Gini scores of about 0.25, comparable to SA 2 sites in Eurasia. Though this was changing rapidly after Δ3000, the overall impression is for relatively flat site hierarchies in the Americas compared to Asia and Europe. This could be a result of higher transport frictions in the Americas, where (with the partial exception of camelids in Andean South America) the animals used in Eurasia for riding and portage were unavailable. This in turn may have minimized movement of bulk goods to higher-ranked settlements; for example, the well-known Classic Maya sites usually have SA < 8 though they display high Gini coefficients (30, 31). One of the clearest patterns in Fig. 1 is for the Americas sequence to be truncated (by European colonizers) around ~Δ4000 in our sample, which contains relatively few sites postdating AD 1500. The European sequence is some 2,000 Δyears longer, and that in Asia, some 4,000 Δyears longer. Perhaps as a result, both site hierarchies

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and Gini coefficients were growing rapidly in the Americas right up to the Conquest, whereas the European sequence underwent prominent declines in site hierarchies and Ginis after Δ5000, and the Asia sequence, after Δ7000. We do not emphasize such terminal variability here because of edge effects: The latest sites have considerable influence on the placement of the loess lines.

***Polity-scale effects.*** Fig. 2 graphs the differences between the loess-fitted central tendencies for Gini coefficients in the Apex and Basal sites from Fig. 1. These "polity-scale effects" (PSE) are due to some combination of agglomeration effects [including concentration of population with attendant opportunities for specialization, knowledge exchange, and innovation (32)], flows of goods toward polity centers due to taxes or tribute (33), and any differential locational advantages for production, trade, or defense contributing to the success of some households (34). PSE values in Fig. 2 reflect the average difference in inequality that would have been experienced in moving from a site at the bottom of the local site hierarchy, to one at the top, as that changed through time.

The World sample (Fig. 2) demonstrates a nearly steady and almost linear increase in PSE for the eight millennia represented in our sample, leveling off only slightly between Δ1000 and Δ2500. Of course, it is only possible to apprehend these changes in hindsight and with the benefit of the last 50 y of archaeological research; the temporal and spatial scales of these shifts greatly exceed human perception. Yet the slowly changing structures of human communities that this measure reflects would have changed lived experiences throughout much of the world.

PSE histories seem to vary greatly across the three macroregions, but some of the obvious differences are due to particular sites near the temporal extremes that are influential in the loess fits. In Asia, PSE values climb steadily from Δ-500 to Δ4500 before leveling off. In Europe, for reasons suggested above, there were almost no Apex sites until ~Δ2500; after that PSE values increased rapidly, reaching the highest PSE value (~0.18) for any of the macroregions before beginning an even more rapid decline. The terminal low Ginis for Europe are derived from post-Roman Saxon settlements of Britain.

In the Americas, the PSE sequence in general shows a strong increase over its five millennia duration, though with a notable pause between Δ1000 and Δ2000. The strong initial increase is due in part to the influence of sites like Kincaid (A.D. 1050/Δ250, Gini 0.6), a Mississippian multimound site in the American Bottom. Such Mississippian sites posed the challenge, in coding, of whether to consider the development of the earlier Eastern Agricultural Complex (EAC) (35) as marking the onset of "common" agriculture or to regard the EAC as inaugurating the "earliest" agriculture in this area, with the latter being adopted. Sites such as Kincaid would appear less anomalous if Δyears indexed earliest agriculture. From Δ2000 to Δ4000 the rate of PSE increase in the Americas is similar to the highest rates observed in Europe.

The timing in Δyears of major increases in PSE is thus somewhat variable across macroregions, proceeding earliest in Asia, later in the Americas, and still later in Europe. Farming set in motion processes that often (but not immediately) resulted in the development of site-size hierarchies, which in turn provided opportunities for wealth differentiation that were more commonly realized in higher-ranked sites. Given the high correlation between SA and the population of the polities in which sites were embedded (*SI Appendix*, Fig. S2), population growth beginning but not ending with the NDT was undoubtedly a key part of this process.

**What Factors Influence Wealth Inequality?** We generated contextual information for the sites whose structure-size differences were just described. These included presence–absence variables such as whether animal husbandry was practiced at the time of site occupation, as well as estimates of site and polity size where these were possible (8). We use Bayesian regression to make probabilistic inferences about the effect of these potential influences on site Gini coefficients (*Materials and Methods* and *SI Appendix*). Fig. 3 presents the models derived, first, for the World sample and then for its subsets from Asia, Europe, and the Americas. Population-level effects (or fixed terms) used in analysis are defined in *SI Appendix*, Table S1; these are assumed to be the same across observations. We represent sites as nested in regions by using Region as a grouping term (or random effect) for all models, allowing the intercepts for each model to vary by Region and accounting for the possibility that sites in the same region will have similar Gini coefficients for any number of reasons. Such models are often called random-intercept models. Inference of change through time within the World sample is developed by

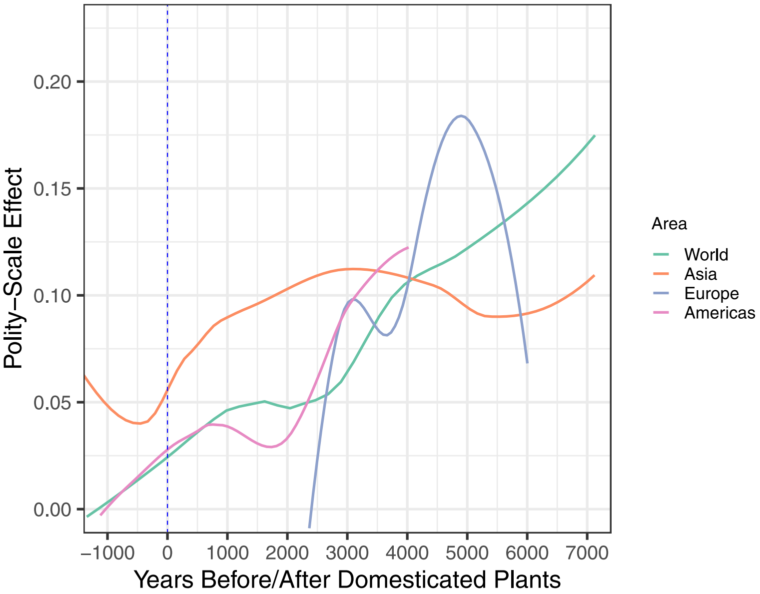

**Fig. 2.** Polity-scale effects: The differences through time, in Δyears, between modeled Gini values for Apex and for Basal sites in the World sample, and by macroregion (data from Fig. 1; loess span 0.9). The vertical line marks onset of common local plant cultivation. Positive values indicate higher house-size-based Gini values for Apex than for Basal sites on average. Sample sizes as in Fig. 3.

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comparing analysis results for the sequential time slices in Fig. 4. We characterize uncertainty about the effects of the predictors of the Gini coefficient using the credible intervals (CIs) in these two figures. Predictors whose 90% CIs exclude 0 are considered to have effect with high probability; variables whose 50% (but not 90%) CIs exclude 0 are considered to have effect with low probability. The remaining fixed effects in the figures are unlikely to influence economic inequality at the temporal scale and spatial scope under analysis. Note that these are all partial correlations, that is, they take into account the effects of the other independent variables in the model. The CIs constitute implicit tests of a very wide range of hypotheses about the structural factors affecting variability of wealth inequality in these ancient societies.

Considering the entire World sample in this cross-sectional approach (Fig. 3), three variables increase housing inequality with high confidence: use of animals for riding, high values for SA (Social Advantage), and high values for Fourscale [a measure of the degree of land limits on production (*SI Appendix*, Table S1)].

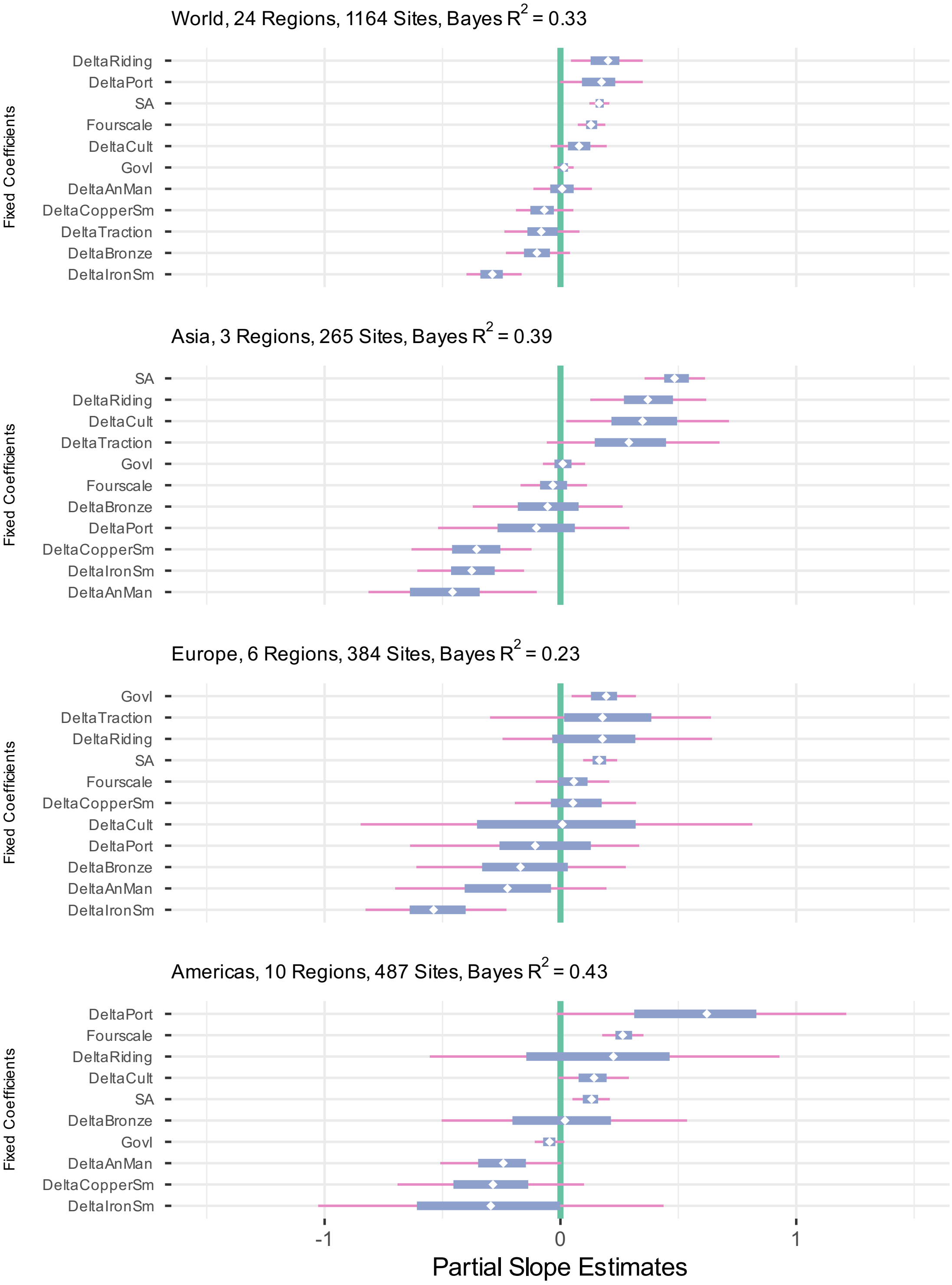

**Fig. 3.** Bayesian multilevel regression model results for the entire sample (World) and the three macroregions with the largest samples. CIs for fixed coefficients are displayed as blue (50%) or red (90%); fixed coefficients ordered by median estimates displayed as white diamonds. Discussion emphasizes coefficients whose CIs do not enclose 0. All models use random intercepts for regions. For statistical details, see *SI Appendix*.

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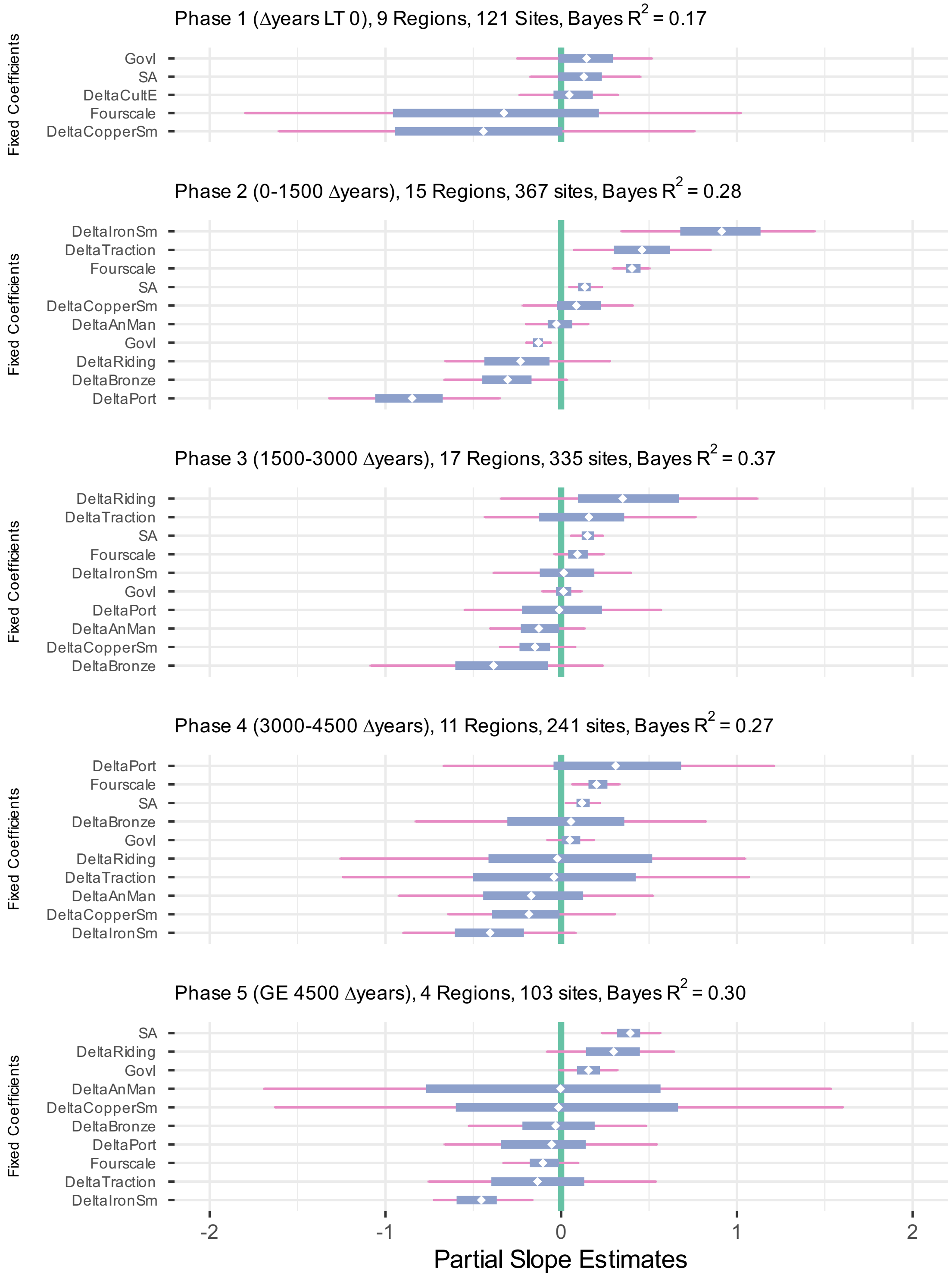

**Fig. 4.** Bayesian multilevel regression model results for five sequential temporal subsets of the World sample. CIs for fixed coefficients are displayed as blue (50%) or red (90%); fixed coefficients ordered by median estimates displayed as white diamonds. Discussion emphasizes coefficients whose CIs do not enclose 0. All models use random intercepts for regions. For statistical details, see *SI Appendix*.

At lower confidence, presence of cultivated plants and use of animals for portage increase Gini values. Iron smelting reduces Gini values (high confidence) as does bronze smelting, use of animals for traction (plowing) and copper smelting (all three with low confidence). The 95% CI for the Bayesian $R^2$ (36) shown in Fig. 3 ranges from 0.29 to 0.37. The contribution of the fixed effects to the total posterior variance is 0.36; the contribution of random intercepts to the total posterior variance is 0.22. The sum of these two proportions, subtracted from 1, indicates the proportion of variance not explained by the model. Unsurprisingly, at the world level, there is a great deal of variability in wealth inequality shared within regions even after accounting for the fixed effects (13).

For Asia, regression identifies three positive fixed effects at high confidence: SA, riding, and presence of cultivated plants; use of animals for traction also contributes to high economic inequality with low confidence. Smelting of iron and copper, and animal management, reduce economic inequality (high confidence). The fixed effects contribution to the total posterior variance is 0.59;

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the random intercepts for the three regions (W Asia and Cyprus, E Asia, and S Asia) contribute 0.30 to the total variance. The 95% CI for the Bayesian $R^2$ ranges from 0.31 to 0.46.

By contrast with Asia the Bayes $R^2$ for Europe is lower (0.23, 95% CI, 0.16 to 0.29) and Europe is extremely homogenous across its six regions (the contribution of fixed effects to the total posterior variance: 0.91; that of the random intercepts, 0.01). In the post-domestication era, which makes up this sample, Europe's regions had very similar baseline levels of social inequality, likely related to the relatively rapid displacement of its Mesolithic foragers by colonizing farmers from the east and south. High values of GovI [indicating centralization of governing function (37)] and SA contribute to high Gini values (high confidence) and presence of traction animals contribute to high Ginis with low confidence. Iron smelting decreases Gini values (high confidence) as does presence of animal management (low confidence).

In the Americas, we distinguish 10 regions. In order of decreasing number of sites in the sample, these are Central Mexico, Southwest NA (North America), Southeast NA, Great Plains, Northwest NA, Maya, Northeast NA, Southern Andes, Central Andes, and Southern Mexico. The contribution of fixed effects to the total posterior variance is 0.86; that of the random intercepts (by region), 0.06. The Bayes $R^2$, 0.43 (95% CI, 0.37 to 0.48) is somewhat higher than for the other macroregions (and significantly higher than for Europe). At high probability Fourscale and SA contribute to high wealth inequality; availability of animals for portage, and plant cultivation, contribute to wealth inequality at lower probability. High values of GovI (centralization), and presence of animal management and copper smelting, decrease wealth inequality (low confidence).

Returning to the World sample, we now examine how the contextual variables in these data are correlated with Gini values in five sequential time slices depicted in Fig. 4 and *SI Appendix*, Figs. S1 and S5–S7.

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**Changing Influences on Housing Inequality through Time.** In general, the 121 pre- or nonfarming sites in the World sample (Phase 1, Fig. 4) have relatively low Gini coefficients (mean = 0.22, s = 0.11). The sample includes 32 sites from the US Great Plains and 31 from East Asia (mostly Jomon) (*SI Appendix*, Fig. S5); examples include Jerf el Ahmar in N Mesopotamia and the Fish Lake site in the American Bottom (many of the sites in this phase are small and known primarily to specialists). The sample also includes 16 settlements of fisher-hunter-gatherer (FHG) societies on the NA Northwest Coast with mid-dates ranging from 1000 BC to AD 910 and Gini values of up to 0.38 (38, 39)]. [Other current research finds even higher Gini values in some FHG societies, for example among very early fortified sites in West Siberia at the end of the seventh millennium BC (40)]. Several fixed effects were removed from this model as inapplicable to this period (DeltaBronze, DeltaPort, DeltaRiding, DeltaTraction, DeltaIron; however, earliest cultivation, CultE, was added.) The Bayes $R^2$, 0.17 (95% CI, 0.06 to 0.30) shows a relatively poor fit and the individual fixed terms in the model do not influence Gini coefficients in this phase (Fig. 4). The contribution of the fixed effects to the total posterior variance is 0.92; the random intercepts contribute 0.05 to the total posterior variance. In the world of hunter-gatherers and incipient farmers, there seems to be little commonality in the processes producing variability in Gini coefficients across regions, at least using the variables coded in these data. The almost complete absence of any land limitations on production (*SI Appendix*, Fig. S7) suggests high levels of mobility generally characterize this phase. Other work has shown that resource distributions are more powerful for explaining hunter-gatherer inequality than the variables available in our data. In particular, higher inequality is expected where resources are predictable and heterogeneously distributed (41). What stand out in our data are the generally low Gini values and the high degree of idiosyncratic variability encountered.

The Phase 2 sample (Δ0 to Δ1500) contains three times as many sites (367) with East Asia (118) and the Southeastern United States (62) particularly well represented; specific examples include Great Zimbabwe in southern Africa and Cahokia in the American Bottom. Most of the sites in our sample from Africa and Oceania fall into this phase (*SI Appendix*, Fig. S5). The mean Gini is 0.25 (s = 0.10), only slightly higher than the values for pre- or nonfarming sites. Fig. 4 identifies four fixed effects that increase values for the Gini coefficient with high probability: presence of iron smelting and of animals for traction, high values of Fourscale, and high values of SA. High values of GovI (indicating centralized decision-making) and presence of animals for portage decrease Gini values (high probability). The presence of bronze smelting and riding may also decrease Gini values (low probability). The model for Phase II exhibits a better fit to the data than that for Phase I, with a Bayes $R^2$ of 0.28 (95% CI, 0.20 to 0.35). The contribution of the fixed effects to the total posterior variance is high (0.87) and that of the random (regional) effects is low (0.03). In the world of early farmers, the social fact of inequality is slightly more salient and much more explicable by nonresource factors than in the world of hunter-gatherers. On average though economic inequality is slow to develop following the arrival or development of agriculture.

The sample from Δ1500 to Δ3000 (Phase 3, Fig. 4) contains 335 sites that as a group exhibit markedly higher and more variable Gini values than the previous phase (mean = 0.33, s = 0.15). This time slice includes 107 sites from Central Mexico and 64 sites from SE Europe (*SI Appendix*, Fig. S5); example sites include Altun Ha in the Maya Eastern Lowlands and Monte Albán in the Valley of Oaxaca. Figs. 1 and 2 and *SI Appendix*, Fig. S5 suggest that the Americas contribute more to the increase in average Ginis in this period than do Asia or Europe. Fig. 4 shows that one fixed effect, SA, increases Gini values in this phase with high probability; presence of riding and high values for Fourscale may also increase Ginis (low probability). Presence of copper and bronze smelting may decrease Gini values (low probability). The Bayes $R^2$ is 0.37 (95% CI, 0.30 to 0.44)—the highest value among the time slices. The contribution of fixed effects to the total posterior variance is 0.87; of the random intercepts, 0.04.

The sample for Phase 4 (Δyears 3000 to 4500) includes 241 sites with strong representation from Britain (157 sites) and the Southern Andes (34 sites) (*SI Appendix*, Fig. S5); examples include Fishbourne Palace in West Sussex and Chan Chan on the north coast of Peru. The mean Gini (0.34) and SD (0.16) are essentially the same as in the previous phase. Fig. 4 identifies high values for Fourscale and SA as increasing Gini values with high probability. With low probability, presence of iron smelting decreases wealth inequality. The overall explanatory ability of this model is less than for the two earlier farming periods (Bayes $R^2$ = 0.27, 95% CI 0.18 to 0.35). The contribution of fixed effects to the total posterior variance is 0.92, and as for the other phases, the contribution of the random intercepts to the total posterior variance is negligible (0.04).

The Phase 5 sample (>Δ4500) is also the smallest (103 sites). Sites in this group exhibit the highest mean Gini (0.37) and also the highest SD (0.19) of the phases analyzed. This sample is dominated by sites from West Asia/Cyprus (52) and SE Europe (28) (*SI Appendix*, Fig. S5); example sites include portions of Babylon in Southern Mesopotamia and Pompeii in the Bay of Naples. The

Americas no longer contribute to the sample. Fig. 4 identifies SA as increasing Gini values with high probability; at low probability, presence of riding and centralized governance also increase Gini values. Presence of iron smelting decreases Gini values (high probability). The Bayes $R^2$ for this model is 0.30, 95% CI, 0.17 to 0.41). As for the other phases, the contribution of the fixed effects to the total posterior variance dominates (0.94) whereas that of the random intercepts (0.03) is negligible.

## Discussion

We describe and analyze economic inequality in the distant past at spatial and temporal scales that have little precedent in data-guided archaeology. The choice of a timescale, Δyears (dates of housing at each site relative to the arrival or development of domesticated plants), implies that the processes analyzed were largely set in motion by plant domestication, which itself was likely assisted by the more favorable climates of the Holocene (42). The fact that significant regularities emerge through time across regions when time is represented in this way underscores the plausibility of this choice. The power of Δyears in setting the pace for increases in wealth inequality around the world is also evident in the much higher contribution of the random intercepts to the total posterior variance for the World model (Fig. 3, 0.22) than for its Δyear-controlled phases (Fig. 4) where they range from 0.03 (Phases 2 and 5) to 0.05 (Phase 1). This indicates that most regional variability in Ginis has been eliminated when global site occupations are synchronized using Δyears. [Borcan et al. (43) similarly demonstrate that variably dated transitions to agriculture pace transitions to statehood.] However, it cannot be domestication itself that leads to inequality because of the lags in increasing inequality following domestication evident in Figs. 1 and 2 and in the samples analyzed by phase in Fig. 4.

Worldwide there is pervasive though not universal evidence for increasing economic inequality some 1,500 y after plant domestication became locally common (somewhat later in Europe, somewhat earlier in Asia). This finding was anticipated by Gurven et al. (44) who noted that "domestication alone does not transform social structure; rather, the presence of scarce, defensible resources may be required before inequality and wealth transmission patterns resemble the familiar pattern in more complex societies." The sequence documented here does however cast doubt on models that require elites to orchestrate the transition to sedentary life and then to farming (as in ref. 45, pp. 138–141), since economic elites (at least) seem to typically emerge long after both transitions.

Shared processes common to most of the world regions and periods analyzed affecting levels of economic inequality include dependence on SA (the different socioeconomic affordances of living in top- vs. bottom-ranked settlements) and on whether land is limiting for production, differentially enforcing more land-intensive strategies (as measured by Fourscale).

Generally speaking, in the several thousand years separating the inception of common plant domestication from the rise of large empires, large settlements exhibit about 10 Gini points more residential inequality than small settlements (Fig. 2). The size of that discrepancy tends to increase through the period this sample encompasses. The importance of SA in this analysis prompts the question as to whether increasing inequality precipitated formation of site hierarchies, or whether site hierarchies themselves produced inequalities. *SI Appendix*, Figs. S2 and S3 show that both settlement hierarchies and land-limited production are positively related to regional population, although land-limited production is also sensitive to resource distributions and balance of population and resources. Together these structural forces tend to induce inequality by simultaneously decreasing the availability of outside options for poorer clients while increasing the importance for protogovernmental activities such as adjudicating disputes—incidentally thereby increasing the social influence and power differentials of the slightly better endowed (see figure 1 in ref. 46). These processes took place in the context of political institutions that were more typically collective than autocratic or centralized (*SI Appendix*, Fig. S6). The empirical connection between low inequality, which characterizes most of our sites until about Δ1500, and low values for GovI (indicating "self-governing" or collective forms), visible in *SI Appendix*, Fig. S6 for this same period is not just historical coincidence. These two forms co-occur because one favors the other (47).

Localization of political processes in the highest-ranked settlements in turn reinforced nascent settlement hierarchies. Those households which could best take advantage of the affordances of the largest settlements were likely, in general, the same that could best overcome the disadvantages imposed by land-limited production. As more hierarchical settlement systems began to form, the movement of some households to larger settlements represented a social upscaling with the potential to break long-established, local face-to-face ties formed in smaller communities on which reciprocity (a force that helps maintain relative equality) depended. It likely also imperiled long-standing institutions promoting leveling, including ritual mechanisms (48, 49). Once these dominance-suppressing mechanisms were weakened, the (almost) inexorable mechanisms of multiplicative processes leading to lognormal distributions of wealth (and high Ginis)—the "rich-get-richer" dynamic—were unleashed (48). We infer that by the Δ1500 to Δ3000 phase material wealth, a form of cultural niche construction, was emerging as the best vehicle for improving reproductive success for many successful households (50). Thus began our pronounced tendency as a species toward accumulation.

Our findings raise important questions for future research. The strong and relatively consistent relationship between SA and Ginis suggests that whatever factors build site hierarchies are similar to the processes that allow wealth differentiation. This invites detailed regional analyses to discriminate among the pathways that could cause wealth differentiation in the highest-SA-ranked sites, including the relative roles of taxes/tribute, scaling factors, and mere advantages of site location. One causal model focusing solely on this final process that anticipates the relationship between increasing values for both SA and Fourscale, and their strong connection to increasing Ginis seen in our data, was proposed by Dow and Reed (51). Assuming heterogeneity in potential agricultural productivity of sites, they propose that elites will be able to claim the best sites and engage clients to farm their lands, who receive food incomes equal to what they could get at lower-quality sites where access remains open. Over time this would result in highest Ginis at the highest SA sites, which in this model must have the best lands.

Another finding of interest is the relatively low power of our models for explaining variability in inequality after Δ3000 (*SI Appendix*, Table S2). Is this due to having omitted variables that became significant by this time? Several candidates, including enslavement, were included in our database but could not be coded consistently, and so were discarded in this analysis as having too many missing values. [Low visibility for housing of the enslaved (52) contributes to this difficulty—*Materials and Methods*; *SI Appendix*, Table S1]. Another possibility is that by this time important but locally specific, episodic historical dynamics were affecting inequality more than they had previously, adding enough noise to weaken these relationships. Likely candidates would include warfare (53) and plagues affecting dense populations (54), both of which could perturb measures

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of inequality without necessarily affecting values for explanatory variables.

The results call into question the easy assumption that key technological innovations such as development of bronze or iron smelting increased wealth inequality. Presence of iron working in particular seems to have had a strong equalizing effect on wealth, suggesting that it often did more to help lower social strata increase production than it did to increase the wealth of elites. [The Southern Korea case is discussed by Kim (55); for China see Feinman (56)]. An alternative (or contributing) possibility, suggested by MacInnes et al. (57), is that since iron armaments and weaponry were cheaper and could be produced in much larger quantities than those of bronze, a much larger proportion of the population could be mobilized in Iron-age than in Bronze-age warfare. Through their military contributions these masses thus gained bargaining power, increasing their relative prosperity and decreasing our measures of wealth inequality. We point out that statistical analyses on this scale help partition out the effects of particular technologies on inequality since their introduction is accompanied by slightly different suites of contextual variables in different regions. In China for example introduction of iron broadly coincided with political unification, growth of markets and communication networks, introduction of standardized weights and measures, and other important innovations (58). Understanding the effects of iron itself by considering that case in isolation would therefore be extremely difficult. Perhaps the contradictory effect noted in Phase 2 (Fig. 4)—where presence of iron increases wealth inequality—indicates that when it is rare, its use had not typically spread to productivity enhancements (or mass mobilizations leading to bargaining advantages). More generally, the occasional differences in sign between the effects of some key variables in different phases and regions (use of animals for portage, for example, decreases wealth inequality on average in Phase 2, but possibly increases it worldwide and in the Americas) caution us that key technologies may have different effects on economic inequality depending on how mature or common they become, the social settings in which they are deployed, or the uses to which they are put.

The times and places displaying low inequality after plant domestication are of special interest, beginning with the Δ0 to Δ1500 time-slice (Fig. 4). North America is noteworthy in this regard because of its distinctive Kuznets relationship (*SI Appendix*, Fig. S8) showing a tendency for the largest houses to be associated with no greater inequality than the smallest. This is (proximately) due to the inclusion of numerous Iroquoian longhouses of relatively similar size dating between AD ~1300 and ~1600. More generally though the Americas are influenced by the unusual trajectory of agriculture and Ginis in eastern NA, where some of the earliest sites with common agriculture in our sample (such as Cahokia) are found in the American Bottom. These have high Gini values, but following the collapse of Cahokia and similar sites Gini values generally declined up until the European conquest, when our sample thins. The US Southwest (the third-largest component of the Americas sample) likewise exhibits generally declining Gini values after Chaco (26). Bogaard et al. (13) consider whether such declines are linked, even more generally, to labor-limited farming systems.

In these and other similar cases, two distinct categories of potential explanations must be considered (12). One is that these economies produced little per-household surplus (59). In some cases this could be due to low production of early farming systems; Bowles suggests that early cereal cultigens were not more productive than foraging (60) and Morris suggests that the energy rate density (61) likely doubled between 9000 and 3000 BC in the SW Asia, with more productive crops making a large contribution [(62) and references therein]. In other cases low surplus could result from climates unfavorable for production [as Gillreath-Brown et al. (63) argue for the post-Chaco US Southwest]. The second category of explanation turns on social (including political) mechanisms for how surplus is distributed. The oft-cited unwillingness to give up the typical egalitarian practices of hunter-gatherers falls into this category. More analysis, based in particular regions and perhaps employing additional proxies will be needed to determine the mix of energetic, normative, sociopolitical, and competitive factors at work in these low Ginis. Just as important are detailed regional analyses to identify the factors driving up the Kuznets relationship outside North America (*SI Appendix*, Fig. S8). We hope this paper helps identify both situations as deserving more attention.

## Conclusions

As extensively documented by historians and economists, the world since the Industrial Revolution has experienced dramatic swings in economic inequality coupled with radical changes in demography and how wealth has been produced (64). The changes in wealth inequality described here were at least as pronounced, but unfolded over millennia rather than 2 to 3 centuries. The vast stretches of the Holocene prior to AD 1, on which we concentrate, reveal distinct trends of increasing inequality (Fig. 1 and *SI Appendix*, Fig. S4). It cannot be concluded, on our evidence, that the development of wealth inequality in prehistory was isolated or rare, as seems to be implied by some recent discussions (24). Nor is it likely, on the evidence presented here, that "before the Industrial Revolution…there was no relationship between mean income and the level of inequality" (7) (*SI Appendix*, Fig. S8) or that "in preindustrial times, there were no systematic forces [affecting economic inequality]: change was driven by the vagaries of accidents, from catastrophic events to those that partially relieved the constraints of subsistence…" (7). On the contrary, we document a largely cumulative process of increases in wealth inequality and, probably, in degree of wealth itself—even admitting such marked reversals as the collapse of the (western) Roman Empire (54). Discerning these relationships and forces, however, requires serious engagement with archaeological data and an appreciation of long time scales. Our account of the growth of wealth inequality (and wealth production more generally) in these data bears an interesting relationship to classic accounts of the development of inequality in the Industrial Revolution (6, 65). In both cases, the movement of population from more rural to more aggregated settings ["globalizations" in Jennings' framing (66)] was key to both increasing wealth, and increasing wealth inequality. This suggests that the long sweeps of our prehistory can (and should) be studied with the same methods, and the same care, as has been devoted to the period initiated by the Industrial Revolution in northwestern Europe and its offshoots. At the same time, the rather marked worldwide patterns noted in this analysis place considerable limits on the particularism and relativism preferred by some archaeologists.

We present strong evidence that a pervasive reworking of settlement structure, partly preceded by, but also accompanying, shifts to more land-intensive strategies of subsistence, together contributed to increasing wealth inequality worldwide. These processes began and had their most important effects on inequality well before writing. This settlement restructuring took place at least partially in delayed response to increased population and sedentism associated with domestication of plants. Following the development of speech and prior to the development of writing, modern transportation, and communication, we suggest this

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restructuring of settlement on the landscape was the most significant rewiring of human interaction networks undertaken by our species, at least in terms of its consequences for inequality. We also present strong evidence that, in many times and places, horseback riding increases housing inequality [whether through its contributions to herding, hunting, or warfare (67, 68)] whereas iron smelting decreases housing inequality. Other factors including the nature of governance, use of animals for portage, and smelting of copper and bronze also affected the degree of wealth inequality in particular times and places. Growth of inequality does not begin with the Holocene or the Neolithic—competition for social status long predates either (24, 69)—nor does the development of economic inequality begin with the written record, Rome, or the Industrial Revolution.

## Materials and Methods

Development of the house-size proxy for assessing economic inequality is in its early stages. Our approach, using cross-sectional data and Bayesian regression, is exploratory. Causal inferences will be strengthened by adding more samples, enabling application of dynamic regression approaches to time-resolved samples from a variety of regions (5) and considering additional proxies.

Gini coefficients in this paper are calculated by site on total area of residential units, including both living and storage areas. Throughout we use the terms "site" and "settlement" interchangeably, and unless otherwise specified wealth inequality, and housing differentials, are treated as synonyms. Gini coefficients computed by site will usually be lower than were those households pooled by region, period, or polity prior to computing the coefficients (70). In the file used here (SiteGiniLevel), Gini values have already been computed using DescTools::Gini in R and "Gini=Gini(TotalAreaHouse, na.rm=TRUE, unbiased = TRUE, conf.level = 0.8, R = 1,000, type = "perc")." This is a sample of convenience, assembled by the regional specialists on this project from data they knew to be available and could access. Known biases include oversampling of those regions for which archaeology is best developed (much of Europe, Southwest Asia, Japan, North America, portions of Mesoamerica, and Andean South America) and underrepresentation of areas where archaeology is relatively poorly developed or where structural evidence is hard to discern (most of the tropics, and large expanses or periods where high-mobility pastoralism or foraging adaptations dominated). We did not systematically attempt to extend our samples for the Americas beyond about AD 1500, or for Eurasia, beyond about AD 1, though much data are available; more samples from Europe (especially northern Europe), China, and South America are readily available but could not be collected within the constraints of this project. Beyond these biases, we acknowledge limitations including probable underestimation of wealth inequality by our proxy for other reasons (10); difficulties in discerning storage spaces in or near residences (71); and inadequacies in the methods available for analyzing sparse time series data and inferring their causal structure (72). Like any single statistical summary of a distribution, the Gini coefficient cannot shed light on such important questions as the emergence of classes, which require more detail on the shape of wealth distributions.

The explanatory variables in the regressions reported in Figs. 3 and 4 are defined in *SI Appendix*, Table S1. Procedures for handling missing values and for deriving the regression results are described in the *SI Appendix*. Basal and Apex sites are also defined more fully in *SI Appendix*.

All scripts and data for replicating the analyses and reproducing main and supplementary figures are provided in this tDAR Project (https://core.tdar.org/project/496853/the-global-dynamics-of-inequality-gini-project).

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**Data, Materials, and Software Availability.** All scripts and data necessary for replicating analyses and reproducing figures are provided as an R script. The data file, SiteGiniLevel, is linked within the script. Some study data are available through deposit in TDAR (https://core.tdar.org/project/496853/the-global-dynamics-of-inequality-gini-project) (73). While the worldwide archaeological site database includes locational information, some of this information is legally restricted in certain countries. These locations will be obscured (generalized) but all other data will be shared.

**ACKNOWLEDGMENTS.** The GINI (Global dynamics of INequalIty) project is organized by the Coalition for Archaeological Synthesis (http://www.archsynth.org/) and the Center for Collaborative Synthesis in Archaeology (https://ibsweb.colorado.edu/archaeology/). We thank the Santa Fe Institute for hosting two GINI project Working Groups, and the Office of the Provost, Washington State University, for support of the first author. H.K. acknowledges support from the Laboratory Program for Korean Studies, Ministry of Education, Republic of Korea and Korean Studies Promotion Service of the Academy of Korean Studies (AKS-2015-LAB-2250001). We thank Tom Dickinson at the Institute of Behavioral Science, University of Colorado Boulder, for designing and populating the initial GINI project database; and we thank the following individuals for their assistance in compiling the data: Andrew D. Gillreath-Brown, Charles Simmons, Kate Collins, Hudson Clemintine Lee, Pertev Basri, Anthony Del Rio, Qimeng Duan, Christina Kohnen, Robert Nyamushosho, Nancy Egan, Luke Auld-Thomas, Claudette Lopez, Iqtadar Alam, Victoria Harbison, Nikki Vellidis, Marie Wittmann, and Todd Whitelaw. We also thank Darcy Bird for assistance with one of the Working Group meetings, and three reviewers for their insightful comments. Finally we gratefully acknowledge the patient efforts of thousands of archaeologists over more than a century in generating the data analyzed here, and our more distant forebears who left their marks on landscapes later to be deciphered.

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