Overkill, Extinction, and the Neolithic Revolution*

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Abstract

This research explores the biogeographical origins of the emergence and spread of agriculture. The theory suggests that mammal species with certain biological traits were more vulnerable to hunting pressure, leading to their extinction. This reduced hunting resources, which in turn pushed humans toward agriculture. To test this hypothesis, I create a measure that captures the loss of hunting resources due to extinction. By using various complementary datasets, controlling for ancient climatic factors, and leveraging certain biological traits that raise extinction risk as exogenous factors, the research shows that the extinction of large herbivores significantly contributed to the Neolithic Revolution.

Keywords: Neolithic Revolution, economic growth, comparative development, biogeography

JEL Codes: N10, O11, O13, O44, Z13

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1 Introduction

Humans relied on hunting and gathering for 95% of the time since the origin of *Homo sapiens* 300,000 years ago (McDougall et al., 2005). The Neolithic Revolution, marking the shift from foraging to farming, is one of the most significant transformations in human history. Agricultural surpluses allowed for the development of non-food-producing classes, which were essential for advancements in writing, science, cities, and military technology (Diamond, 1997). The transition to agriculture preceded the rise of states worldwide (Borcan et al., 2021). It spurred the evolution of human traits such as preferences for quality over quantity and increased longevity (Galor and Moav, 2002; Galor and Moav, 2007).[1] The Neolithic Revolution had a profound influence on human history and is at the root of global inequality due to its effects on culture and institutions (Galor, 2022). Despite its importance, we still lack a full understanding of its origins, owing to its complexity and limited data. The reasons behind the Neolithic transition remain one of the most intriguing questions in human prehistory (Price and Bar-Yosef, 2011).

This research explores the biogeographical origins of the Neolithic Revolution both theoretically and empirically. The model suggests that, without secure property rights, people overhunted mammals, leading to a sharp decline in hunting yields and driving the shift toward farming. It shows that some mammals were particularly vulnerable to hunting pressure due to biological traits that made them easier to catch, resulting in their extinction and facilitating the transition to agriculture. The research also addresses a key question about the Neolithic Revolution: Why did early farmers adopt agriculture, despite its higher labor demands and lack of immediate consumption benefits? While existing studies that emphasize the advantages of farming don't fully explain this shift, the extinction theory provides a clear answer.

To empirically test the theory's predictions, I construct a measure of the loss in hunting

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[1] For more on the impact of the Neolithic Revolution on socioeconomic outcomes and human development, see Hibbs and Olsson (2004), Olsson and Hibbs Jr (2005), Putterman (2008), and Dickens and Lagerlöf (2021), among others.

returns due to extinction, using several new datasets on mammal species. I find a robust association between the loss of hunting returns and the Neolithic transition, confirmed across various datasets and variations in both the transition and extinction. To better identify human-driven extinction and get closer to causality, I directly control for paleo-climatic factors and apply an instrumental variable approach, using plausibly exogenous biological traits that increase extinction risk.

I construct a measure of lost biomass, reflecting the reduction in hunting returns, by using the predicted spatial distribution of mammal species and their extinction status. The Phylogenetic Atlas of Mammal Macroecology (PHYLACINE) database (Faurby et al., 2018) provides data on the spatial distribution of all known mammal species since the Last Interglacial.[2] For each species, the database provides a range map that estimates where they would live today if not impacted by human activities. To construct biomass, I use the well-established relationship between body mass and population density,[3] and I determine the extinction status of species using data from Andermann et al. (2020). This allows me to calculate how much biomass was lost due to mammal extinctions.

Paleo-climatic factors are crucial for both identification and causality, so I account for them, along with other potential confounding factors. It is widely recognized that humans, climate, or both were the main drivers of mass extinction over the last 120,000 years, with other factors playing little to no role (Stuart, 2015).[4] By controlling for paleo-climatic factors, I can more confidently attribute extinction to human causes. Climate has also been viewed as an important factor in the agricultural transition (Dow et al., 2009; Ashraf and Michalopoulos, 2015; Matranga, 2024), so controlling for these factors helps reduce concerns about spurious correlations.

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[2] The Last Interglacial was a warm period between approximately 129,000 and 116,000 years ago, preceding the most recent glacial period (the last Ice Age).

[3] Specifically, I use this relationship to estimate species abundance, which is essential for calculating biomass. The association between population density and body mass is well-documented in the field of allometry (Peters and Raelson, 1984; Damuth, 1987; Silva and Downing, 1995; Silva et al., 2001).

[4] Recent studies increasingly point to human activity as the primary cause of extinction, rather than climate (Sandom et al., 2014; Faurby and Svenning, 2015; Araujo et al., 2017; Andermann et al., 2020; Lemoine et al., 2023).

Institutions and culture of local foraging groups may have influenced both extinction and the agricultural transition. To address this, I use an instrumental variable approach. The instrument replaces the *actual* extinction status with the *predicted* extinction probability, which is based on plausibly exogenous biological traits that increase extinction risk. In particular, I use species' limb morphology and digestive systems. Limb types affect running speed and agility, leading to differences in a species' ability to escape hunters. Digestive systems determine how much time and how often mammals need to feed, affecting their exposure to hunters. As a result, species with less efficient limb types and digestive systems are more likely to go extinct. These traits evolved long before humans appeared, making them plausibly pre-determined.

To establish the impact of extinction on the Neolithic transition, I use various datasets with different units and variations that complement each other. A cross-country analysis offers a global view of the relationship between biomass loss and the timing of the transition. This analysis controls for paleo-climatic factors, continent fixed effects, and various geographical features. Both ordinary least squares (OLS) and two-stage least squares (2SLS) regressions show a strong and robust link between lost biomass and the transition.

Since modern country borders are not relevant to the agricultural transition in (pre)historical times, the timing of the transition at the country level is often noisy. To address this, I supplement the analysis with data from Neolithic archaeological sites. Using information on Neolithic settlements in Europe, the Middle East, East Asia, and Southeast Asia, I create a $1^\circ \times 1^\circ$ grid cell. I construct a panel data on archaeological sites at this grid cell level. The panel analysis, which controls for paleo-climatic factors, as well as cell and time fixed effects, shows a strong relationship between biomass loss and the likelihood of the transition. The 2SLS estimate reveals a strong impact, indicating a significant economic effect of the extinction.[5]

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[5] I also conduct a cross-archaeological site analysis using 1-degree by 1-degree grid cells and find a strong positive link between lost biomass and the timing of the Neolithic transition. This result holds for both OLS and 2SLS estimates and remains robust when controlling for paleo-climatic factors and various geographical features. I present this result in the appendix.

Finally, I conduct a panel analysis focusing solely on the variation in independent transitions to agriculture worldwide. Unlike the cross-country and archaeological-site analyses, this approach examines the impact of biomass loss on the emergence of agriculture, rather than its spread. Using data from well-established sites of pristine agricultural transitions, I create a $1^\circ \times 1^\circ$ grid cell panel. Both OLS and 2SLS analyses, which control for paleo-climatic factors, as well as cell and time fixed effects, reveal a strong link between biomass loss and the likelihood of *independent* agricultural transitions.

This research contributes to the multidisciplinary literature on the origins of agriculture.[6] The first economic study, by Smith (1975), examined the economic incentive to overhunt prey animals and linked their extinction to the agricultural transition in the Americas. Dow et al. (2009) theorize that agriculture emerged in areas that experienced an initial climatic improvement followed by a reversal. Ashraf and Michalopoulos (2015) show a hump-shaped relationship between climate volatility and the timing of the agricultural transition. Matranga (2024) show that climatic seasonality encouraged sedentary settlements, promoting the transition to agriculture. Bowles and Choi (2019) suggest that farming helped stabilize private property, which facilitated the agricultural transition. Riahi (2020) find an inverted U-shaped relationship between large mammal extinction and the likelihood of pristine agriculture. Finally, Grall et al. (2024) find a theoretical and empirical link between somatic capital and the timing of the Neolithic transition.

This paper also contributes to the literature on the deep-rooted determinants of comparative development, particularly studies on biogeographical origins. Diamond (1997) highlights the role of domesticable animals and plants in the rise of agriculture, institutions, and states. Olsson and Hibbs Jr (2005) theoretically and empirically support Diamond's hypothesis, providing evidence for the influence of biogeographical conditions. Link (2024) shows that transport mammals promoted long-distance trade and the development of social hierarchies.

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[6] The origins of agriculture are a widely debated topic across fields such as economics, evolutionary biology, archaeology, and anthropology (for surveys, see Weisdorf, 2005; Price and Bar-Yosef, 2011).

This research contributes to the literature by providing strong evidence that the extinction of large herbivores led to the emergence and spread of agriculture. It develops a long-run economic growth model that links biological traits making mammals vulnerable, their extinction, and the Neolithic transition. The study introduces various datasets on mammal species. Using these datasets, I create a measure of hunting loss due to extinction and an instrumental variable for extinction, both of which are available in cross-sectional and panel analyses at various spatial scales.

The rest of the paper is structured as follows. Section 2 develops the model of the transition from foraging to agriculture. Section 3 describes the datasets and the construction of key variables. Section 4 presents the empirical evidence. Section 5 offers concluding remarks. Online Appendix A provides historical background.

2 The Model

This section outlines a theory explaining the shift from hunting to agriculture. It argues that the extinction of large mammals drove this transition, emphasizing the role of biological vulnerability in the rise of farming. The theory also includes Malthusian pressure, making population growth an internal factor. It provides a clear explanation for why early farmers adopted agriculture, despite the increased labor and lack of immediate food benefits.

Consider an overlapping-generations economy operating over infinite discrete time, composed of multiple species of megaherbivores. Each period, the economy produces a single homogenous good using two production methods: hunting (sector h) and agriculture (sector a). Hunting uses land, biomass, and labor, while agriculture uses land and labor. Land supply is fixed and exogenous, while biomass is a renewable resource. Labor is allocated based on the relative productivity of the two sectors.

2.1 Production of Final Output

In the hunting sector, output at time t, Y_t^h, follows a Cobb-Douglas function:

$$Y_t^h = A^h (B_t X^h)^\alpha (L_t^h)^{1-\alpha}, \tag{1}$$

where A^h is the technological level, B_t is the biomass stock, X^h is the land used (normalized to 1), L_t^h is the labor force, and $\alpha \in (0, 1)$.

The focus is on megaherbivores[7] as prey, as they provided more economic value and nutrition than smaller mammals. Non-herbivores were likely too dangerous for early hunters and reasonably they were not prey mammals.[8] Thus, the biomass B_t represents megaherbivore biomass.

Output per hunter at time t, y_t^h, is:

$$y_t^h = A^h B_t^\alpha (L_t^h)^{-\alpha}. \tag{2}$$

In the agricultural sector, land was abundant during the transition, leading to constant returns to labor.[9] The output at time t, Y_t^a, is:

$$Y_t^a = A_t^a X^a L_t^a, \tag{3}$$

where A_t^a is the technological level, X^a is the land used, and L_t^a is the labor force. Output per farmer, y_t^a, is:

$$y_t^a = A_t^a X^a. \tag{4}$$

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[7] The formal definition of megaherbivores is herbivores larger than 44 kg. This threshold is standard in the definition of megafauna, which are large terrestrial mammals (Faurby and Svenning, 2015).

[8] Hart (2018) provide examples of non-herbivores, such as lions, tigers, and bears, hunting humans. While most cases are modern, they suggest that prehistoric humans faced a much higher risk of being hunted by these dangerous mammals, especially since there were more such predators and humans had less advanced weapons and shelters.

[9] This assumption has been widely accepted in the related literature (Weisdorf, 2005).

When agriculture is not economically viable, there is no technological progress in that sector. However, once cultivation occurs, it starts gradually increasing through learning by doing (Dow et al., 2009).[10] Hence, growth of agricultural technology is modeled as

$$A^a_{t+1} = F(A^a_t, L^a_t), \tag{5}$$

where $A^a_{t+1} = F(A^a_t, L^a_t) = A^a_t$ if $L^a_t = 0$, and $\partial F(A^a_t, L^a_t)/\partial L^a_t > 0$ if $L^a_t > 0$. Thus, when agriculture is latent, its productivity remains constant. When it is active, its productivity increases, especially when more labor is employed in it.

2.2 Evolution of the Biological Stock

In a natural equilibrium, biomass remains stable at the maximum level that the regional ecosystem can support. However, when humans hunt mammals, this reduces the overall biomass. Since biomass is a replenishable biological resource, it recovers and moves back toward its natural level after some depletion. However, if too much is lost, the system may no longer be able to replenish itself. Hence, the law of evolution of biomass is

$$B_{t+1} = \begin{cases} B_t + \kappa(v)(\overline{B} - B_t) - A^h B_t^{\alpha}(L^h_t)^{1-\alpha} & \text{if } \; B_t > B^*(v) \\ B_t - A^h B_t^{\alpha}(L^h_t)^{1-\alpha} & \text{if } \; B_t \leq B^*(v), \end{cases} \tag{6}$$

where κ is the rate of replenishment, $\overline{B}$ is the highest level of biomass sustained in a natural equilibrium, B^* is the threshold below which biological resources are not self-supported, v is the degree of biological vulnerability of mammals.

As long as biomass in period t, denoted as B_t, remains above the biological threshold B^*, the biomass will recover at the natural replenishment rate $\kappa(v)$, while simultaneously

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[10] Dow et al. (2009) discuss how agricultural technology improved through learning by doing. Examples include optimizing planting and harvesting times, seed spacing, weeding, fertilizing, irrigation, and selecting plant traits. In contrast, learning by doing had a much smaller role in the hunting sector. While including the evolution of hunting productivity would add complexity, it does not affect the qualitative results, so I do not model it explicitly.

decreasing by the amount of hunting, represented by $A^h B_t^{\alpha}(L_t^h)^{1-\alpha}$. Therefore, the change in biomass in the next period depends on the balance between biological recovery and the impact of hunting. However, once biomass falls below the biological threshold, the natural birth rate drops below the natural death rate (Koch and Barnosky, 2006), preventing any recovery toward the natural equilibrium. If humans continue hunting mammals, biomass will continue to decline in proportion to the hunting yield.

Let $\mathcal{J}$ represent the set of species in the economy, where each species $j \in \mathcal{J}$ has its own biological vulnerability, denoted as v_j. The overall vulnerability of the economy is an aggregated measure of the vulnerabilities of all species and can be expressed $v = \mathbf{E}[v_j] = \frac{1}{N}\sum_{j\in\mathcal{J}} v_j N_j$, where N_j is the number of individuals of species j and $N = \sum_{j\in\mathcal{J}} N_j$. High vulnerability indicates biological features lowering reproductive success.[11] Consequently, the replenishment rate κ is a decreasing function of v. Furthermore, once biomass falls below the biological threshold B^*, it can no longer self-replenish. Therefore, economies with higher biological vulnerability are more likely to cross this critical threshold.

Hence, I assume

$$\frac{\partial \kappa(v)}{\partial v} < 0 \ \ \textit{and} \ \ \frac{\partial B^*(v)}{\partial v} > 0. \tag{7}$$

2.3 Preferences and Constraints

In each period t, a generation consisting of L_t identical individuals joins the labor force. Each individual has a single parent, and members of generation t live for two periods. In the first period (childhood), $t-1$, individuals are economically inactive. In the second period (adulthood), t, individuals are endowed with one unit of time, which they optimally allocate between child-rearing and labor force participation.

The preferences of members of generation t are defined over consumption, leisure, and

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[11] These are, for example, longer gestation periods, longer maternal care periods, older age at sexual maturity, inefficient digestive systems, and inefficient limb morphology.

the number of their children. Their utilities are represented by the function

$$u_t = (1-\gamma)(\ln c_t + \beta \ln l_t) + \gamma \ln n_t, \tag{8}$$

where c_t is the consumption of an individual of generation t, l_t is the leisure time, n_t is the number of children, and $\gamma, \beta \in (0,1)$.

Income for a member of generation t, y_t, is the amount earned by supplying labor to the sector that produces higher output per individual. Child-rearing is costly and requires a fraction p of parental income per child. Individuals spend their time on work, child-rearing, and leisure. They use the income for consumption. Thus, in the second period of life, the individual faces the budget constraint

$$c_t \leq y_t(1 - pn_t - l_t), \tag{9}$$

where $y_t = \max\{y^h(B_t, L_t^h; A^h), y^a(A_t^a, X^a)\}$.

2.4 Optimization

Members of generation t choose their number of children, leisure time, and their own consumption to maximize their utility function subject to the budget constraint and subsistence-consumption constraint. Substituting (9) into (8), the optimization problem of a member of generation t is

$$\begin{aligned} &\underset{n_t, l_t}{max} && (1-\gamma)\ln y_t(1-pn_t-l_t) + (1-\gamma)\beta \ln l_t + \gamma \ln n_t \\ &\textit{subject to} && y_t(1-pn_t-l_t) \geq \tilde{c}; \\ & && n_t, l_t \geq 0. \end{aligned} \tag{10}$$

Let $\tilde{y}$ be the level of income above which the subsistence constraint is not binding; that is, $\tilde{y} = \tilde{c}[1 + (1-\gamma)\beta]/(1-\gamma)$. Define worktime as $w_t = 1 - pn_t - l_t$. It follows that for

$y_t \geq \tilde{c}$,

$$(c_t^*, n_t^*, l_t^*, w_t^*) = \begin{cases} \left(\frac{1-\gamma}{1+\beta-\gamma\beta} y_t, \frac{\gamma}{p(1+\beta-\gamma\beta)}, \frac{\beta(1-\gamma)}{1+\beta-\gamma\beta}, \frac{1-\gamma}{1+\beta-\gamma\beta}\right) & \textit{if} \quad y_t \geq \tilde{y} \\ \left(\tilde{c}, \frac{\gamma}{p[\gamma+\beta(1-\gamma)]}\left(1-\frac{\tilde{c}}{y_t}\right), \frac{\beta(1-\gamma)}{\gamma+\beta(1-\gamma)}\left(1-\frac{\tilde{c}}{y_t}\right), \frac{\tilde{c}}{y_t}\right) & \textit{if} \quad y_t \leq \tilde{y}. \end{cases} \tag{11}$$

As long as the income of a member of generation t is below $\tilde{y}$, the subsistence consumption is binding. As y_t increases (but remains below $\tilde{y}$), the individual spends a larger fraction of income for child rearing and leisure while maintaining subsistence consumption. As a result, they work less as they earn more income. In contrast, when y_t is larger than $\tilde{y}$, the number of children, leisure, and worktime are constant while an increase in income is devoted to consumption.

The focus of the model is the transitional phase from foraging to agriculture, and this period is governed by the Malthusian mechanism, in which the subsistence constraint is binding and the income elasticity of demand for children is positive. Therefore, I assume

$$\tilde{c} \leq y_t \leq \tilde{y}. \tag{12}$$

2.5 Evolution of the Population

The evolution of the working population over time is

$$L_{t+1} = n(y_t) L_t, \tag{13}$$

where $L_t = L_t^h + L_t^a$ is the size of the population in period t. Given the optimal fertility choice, (11), and the Malthusian regime, (12), the dynamics of the population become

$$L_{t+1} = \frac{\gamma}{p[\gamma + \beta(1-\gamma)]}\left(1 - \frac{\tilde{c}}{y_t}\right) L_t. \tag{14}$$

2.6 The Dynamic System

The development of the economy is governed by the endogenous evolution of the biological stock, the size of the population, and the level of agricultural technology. Therefore, the dynamics of the economy are fully determined by the sequence $\{B_t, L_t, A_t^a\}_{t=0}^{\infty}$ that satisfies (5), (6) and (14).

2.6.1 The Replacement Frontier

The *Replacement Frontier* is the geometric locus of (B_t, L_t) such that, given the latency of agriculture (that is, $y^h(B_t, L_t; A^h) > y^a(A_t^a, X^a)$), the fertility rate of members of generation t is at the replacement level (that is, $n(y_t) = n[y^h(B_t, L_t; A^h)] = 1$).

Hence, using (11), the set of (B_t, L_t) on the Replacement Frontier is expressed as

$$LL \equiv \left\{ (B_t, L_t) : L_t = \left(\frac{A^h}{\tilde{c}} \left(1 - \frac{p\,(\gamma + \beta(1-\gamma))}{\gamma} \right) \right)^{\frac{1}{\alpha}} B_t \right\}. \tag{15}$$

Let (B_t^{LL}, L_t^{LL}) represent the biomass and population size at time t in LL. Then, $\partial n(y_t)/\partial y_t > 0$, $\partial y^h(B_t, L_t; A^h)/\partial L_t < 0$, and (14) determine the evolution of population size, summarized in the following lemma:

Lemma 1 *Given* (B_t, L_t), A^h, *and* A_t^a *such that* $y^h(B_t, L_t; A^h) > y^a(A_t^a, X^a)$,

$$L_{t+1} \gtreqqless L_t \Leftrightarrow L_t \lesseqqgtr L_t^{LL}. \tag{16}$$

2.6.2 The Biologically Stable Frontier

The *Biologically Stable Frontier* is the geometric locus of (B_t, L_t) such that, given the latency of agriculture, the biological resource is at the equilibrium level (that is, $\Delta \equiv B_{t+1} - B_t = 0$).

For $B_t > B^*$, using (6), the set of (B_t, L_t) on the Biologically Stable Frontier is given by

$$BB \equiv \left\{ (B_t, L_t) : L_t = \left[\frac{\kappa(v)}{A^h} \right]^{\frac{1}{1-\alpha}} B_t^{-\frac{\alpha}{1-\alpha}} (\overline{B} - B_t)^{\frac{1}{1-\alpha}} \right\}. \tag{17}$$

For $B_t \leq B^*$, it is given by $L_t = 0$ or $B_t = 0$.

Let (B_t^{BB}, L_t^{BB}) represent the biomass and population size at time t in BB. For $B_t > B^*$, it follows that:

$$\frac{\partial L_t^{BB}}{\partial B_t^{BB}} < 0, \quad \frac{\partial^2 L_t^{BB}}{\partial (B_t^{BB})^2} > 0, \quad \text{and} \quad \frac{\partial L_t^{BB}}{\partial v} < 0. \tag{18}$$

Thus, the Biologically Stable Frontier for $B_t > B^*$ forms a strictly convex, downward-sloping curve, shifting downward as v increases.

The evolution of biomass, as determined by (6), is summarized in the following lemma:

Lemma 2 *Given* (B_t, L_t), A^h, *and* A_t^a, *for* $B_t > B^*$,

$$B_{t+1} \gtreqless B_t \Leftrightarrow B_t \lesseqgtr B_t^{BB}.$$

For $B_t \leq B^*$, $B_{t+1} < B_t$.

2.6.3 The Hunting-Farming Frontier

The *Hunting-Farming Frontier* is the geometric locus of (B_t, L_t) such that, given exclusive employment of the labor force in the hunting sector (that is, $L_t = L_t^h$), a member of generation t is indifferent between supplying their labor to the hunting sector and supplying it to the agricultural sector (that is, $y^h(B_t, L_t; A^h) = y^a(A_t^a, X^a)$).

Hence, using (2) and (4), the set of (B_t, L_t) on the Hunting-Farming Frontier is given by

$$yy \equiv \left\{ (B_t, L_t) : L_t = \left(\frac{A^h}{A_t^a X^a} \right)^{\frac{1}{\alpha}} B_t \right\}. \tag{19}$$

Let (B_t^{yy}, L_t^{yy}) be the pair of biomass and population size at time t in yy. Taking the first derivative with respect to A_t^a yields

$$\frac{\partial L_t^{yy}}{\partial A_t^a} < 0. \tag{20}$$

Since $\partial y^h(B_t, L_t; A^h)/\partial L_t < 0$, (2) and (4) determine the relative average productivity of hunting compared to agriculture, as summarized in the following lemma:

Lemma 3 *Given* (B_t, L_t)*,* A^h*, and* A_t^a*,*

$$y^h(B_t, L_t; A^h) \gtreqless y^a(A_t^a, X^a) \Leftrightarrow L_t \lesseqgtr L_t^{yy}. \tag{21}$$

Lemma 3 implies the existence of a threshold level of L_t, uniquely determined by each B_t, beyond which agriculture becomes a more favorable mode of subsistence than hunting. It further suggests that the relationship defining this threshold is expressed by the functional form in (19).

Finally, the relationship between the Replacement Frontier, the Hunting-Farming Frontier, and individual fertility is summarized in the following lemma, using (4), (15), and (19):

Lemma 4 *Given* (B_t, L_t)*,* A^h*, and* A_t^a*,*

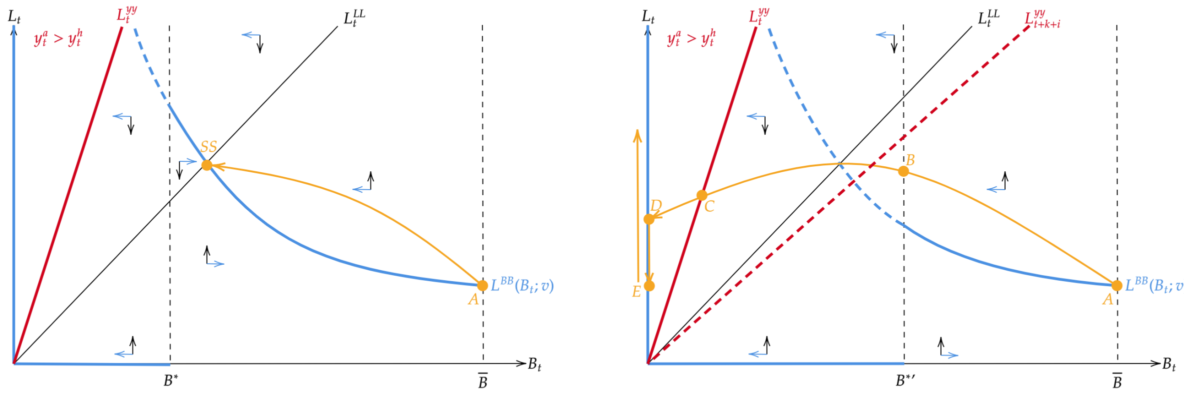
$$y^h(B_t^{LL}, L_t^{LL}; A^h) \gtreqless y^a(A_t^a, X^a) \Leftrightarrow L_t^{yy} \gtreqless L_t^{LL} \Leftrightarrow n\left[y^a(A_t^a, X^a)\right] \lesseqgtr 1. \tag{22}$$

Initially, agriculture is unproductive, not economically viable, and the population size is small. While agriculture remains latent, there is no technological improvement, so agricultural technology at time t stays at its initial level. Therefore, I assume that as long as agriculture is latent, $n[y^a(A_t^a, X^a)] < 1$.

2.7 Transition to Agriculture

This section examines the effects of mammal extinction and biological vulnerability on the timing of the agricultural transition, building on the framework established in the previous subsections.

2.7.1 The Effect of Extinction on the Agricultural Transition



(i) No Extinction

(ii) Extinction

Figure I: The Effect of Extinction

Figure I illustrates the Replacement Frontier, the Biologically Stable Frontier, the Hunting-Farming Frontier, and an economic trajectory, highlighting the role of extinction in the transition to agriculture. Since $\overline{B}$ represents the maximum sustainable biomass, it is the natural starting point. Thus, the economy begins at $A = (B_0, L_t^{BB}(B_0))$, where $B_0 = \overline{B}$. As shown in Lemmas 1 and 2, starting from A, the economy moves towards the upper-left corner, with biomass declining and population growing.

In panel (i), the economy reaches a steady state before hitting the extinction threshold B^*, avoiding mammal extinction. In panel (ii), the economy crosses this threshold at B, causing a shift. Biomass continues to decline as the population grows, eventually crossing the Replacement Frontier. With declining biomass, hunting becomes increasingly unsustainable, and the population shrinks further. The economy reaches point C, where agriculture becomes viable (Lemma 3). Initially, the population keeps declining due to low agricultural productivity while hunting persists. By point D, all available mammals are lost. Over time, learning by doing boosts agricultural productivity (5), and at point E, it surpasses the fertility threshold, enabling population growth again.[12] Ultimately, agriculture becomes the

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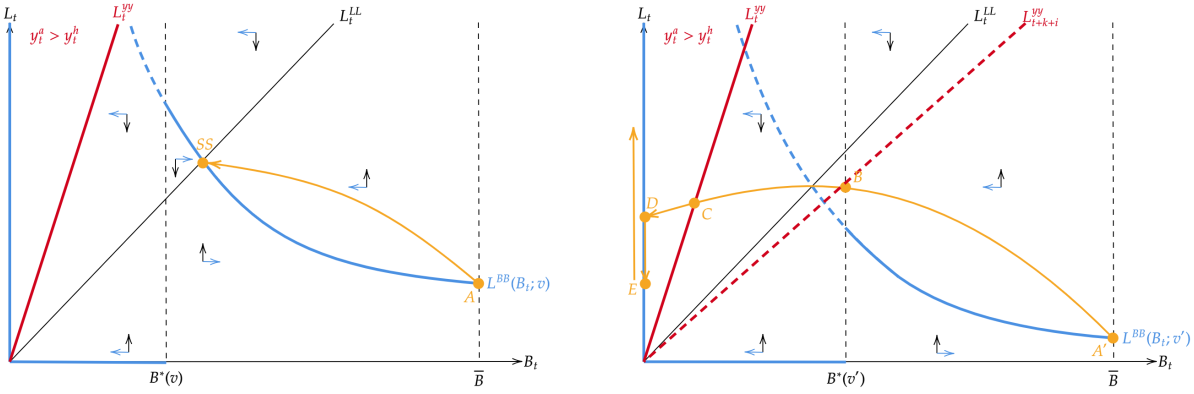
[12] Agricultural productivity could reach this level at any point between C, D, and E; E is simply illustrative. However, mammal extinction is inevitable as hunting continues and biomass fails to recover

dominant subsistence strategy.[13]

2.7.2 The Effect of Biological Vulnerability on the Agricultural Transition



(i) Low Vulnerability

(ii) High Vulnerability

Figure II: The Effect of Biological Vulnerability

Figure II illustrates how mammals' biological vulnerability affects the agricultural transition. In panel (i), an economy with low vulnerability is resilient to hunting pressure, reaching a steady state SS without extinction. In contrast, panel (ii) shows a more vulnerable economy. Due to greater sensitivity to hunting pressure, (7) and (18), the biological threshold B^* shifts right, and the Biologically Stable Frontier L_t^{BB} shifts downward. As a result, the economy crosses the threshold, leading to extinction. Similar to the previous subsection, some individuals switch to cultivation at point C, and over time, learning by doing makes agriculture the dominant subsistence strategy.

2.8 Testable Implications

The model's testable predictions are summarized in the following proposition:

Proposition 1

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(6).

[13] Without agricultural progress, the economy would converge to a steady state with zero biomass and population.

(i) If the economy experiences significant biomass loss due to megaherbivore extinction, an agricultural transition will occur.

(ii) If the economy is characterized by high biological vulnerability, which increases the extinction risk of mammals, an agricultural transition will occur.

The biological vulnerability of mammals influences the agricultural transition solely through the risk of extinction. Therefore, in the empirical section, I utilize this theoretical linkage to implement a two-stage least squares (2SLS) regression.

Proposition 2 in Online Appendix B shows that the first farmers worked longer than their foraging predecessors, consistent with archaeological and ethnographic studies (Armelagos and Cohen, 1984; Sahlins, 1972). While not a central result of this paper, this helps explain one puzzle of the Neolithic Revolution: Why did early farmers adopt agriculture despite increased labor without a rise in food production? Overhunting led to the extinction of key mammal species, reducing the returns from hunting. As a result, some individuals began cultivating crops, even though their yields were lower than what foragers had once enjoyed. In a Malthusian economy, with a positive demand for both children and leisure[14], declining incomes forced early farmers to work harder despite no immediate increase in food availability.

3 Data and Variable Construction

In this section, I present data on the timing of the Neolithic Revolution, the distribution of prehistoric mammal species, their extinction status, biological traits, and paleo-climatic characteristics. I also explain how to calculate the lost biomass due to mammal extinction. To address concerns about the endogeneity of extinction, I use an instrument that replaces actual extinction status with predicted extinction risk in the lost biomass measure. I also describe how this instrument is constructed.

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[14] This characteristic is derived in (11). Sahlins (1972) provides examples and illustrates the relationship between food gains and work time, supporting this argument.

3.1 Dependent Variable: The Neolithic Revolution

Country-level data on the timing of the Neolithic Revolution come from Borcan et al. (2018), who updated and corrected the original data from Putterman and Trainor (2006). By compiling region- and country-specific archaeological studies, they provide the earliest dates when populations obtained over half of their calories from cultivated foods and domesticated animals. Figure CI shows the global distribution of years since the Neolithic Revolution. There is significant variation, with the earliest transitions in the Middle East, followed by South Asia, East Asia, and Europe. The Americas, Southeast Asia, and North Africa transitioned later, while sub-Saharan Africa and Oceania were the last to transition.

While these data offer the broadest spatial coverage of the agricultural transition, they are a noisy proxy for actual timing, as the ideal unit would be at the human settlement level rather than the country level. To address this, I examine variation in the agricultural transition across archaeological sites, using data from Pinhasi et al. (2005) and Cobo et al. (2019).[15] These sources report radiocarbon dates from sites in the Middle East and Europe (Pinhasi et al., 2005) and in East and Southeast Asia (Cobo et al., 2019). Figure CII shows the spatial distribution of these sites. Although the coverage is limited, the data provide more accurate information on the timing of the agricultural transition.

To capture the association between megaherbivore extinction and the emergence of agriculture rather than its diffusion, I also exploit information on independent centers of plant domestication as reported by Larson et al. (2014) (Figure CIII). Relying on genetic, molecular, and archaeological research, they provide information on places and timing of independent plant domestication.

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[15] Data from Pinhasi et al. (2005) have been used in previous economics studies (Ashraf and Michalopoulos, 2015; Matranga, 2024; Olsson and Paik, 2020; Dickens and Lagerlöf, 2021), and Grall et al. (2024) incorporate data from Cobo et al., 2019.

3.2 Independent Variable: Lost Biomass

This subsection introduces a measure of lost biomass from megaherbivore extinction, applicable at various scales such as country, archaeological site, grid cell, and ethnic homeland. The measure is based on data regarding (i) the distributions of mammal species that would exist without human influence, (ii) their body mass and abundance, and (iii) their extinction status.

The PHYLACINE database, compiled by Faurby et al. (2018), provides spatial distribution data for 5,831 known mammal species that have lived since the Late Pleistocene (about 130,000 years ago to present).[16] It includes detailed species characteristics like mean adult body mass, diet, and habitat. A key advantage is its predicted global maps showing where species would live without human influence. Using predicted, rather than current, distributions is important for two reasons: it allows identification of species' prehistorical ranges to calculate biomass, and it reduces concerns about reverse causality from agriculture to mammal distribution.

For extinct mammal species, I use data from Andermann et al. (2020), which provides extinction dates for each species reported in the PHYLACINE. These dates are based on a detailed literature review, using the youngest fossil evidence or last recorded sighting, and are adjusted for sampling errors like preservation bias. I manually matched species between PHYLACINE and Andermann et al. (2020), with 337 out of 352 extinct species (96%) exactly matched.

For a given species, biomass is the product of average body mass and abundance. To estimate abundance, I rely on the well-established negative log-log relationship between body mass and population density (Peters and Raelson, 1984; Damuth, 1987; Silva and Downing, 1995; Silva et al., 2001).[17] To calculate population density, and therefore abundance, I apply the regression from Silva and Downing (1995): $\log_{10}(\textit{Population Density}) =$

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[16] This database is used in economics by Kumagai (2021), (2024) and Link (2024).

[17] This method is commonly used in paleoecology to estimate prehistoric species abundance (Byers and Ugan, 2005; Barnosky, 2008 among others).

$-0.44 \log_{10}(\mathit{Body\ Mass}) + 1.01$.[18]

Using the prehistoric distribution, average body mass, and predicted abundance of each species, I construct a measure of lost biomass due to megaherbivore extinction. For the cross-sectional analysis, the measure is calculated as follows:

$$\mathit{LostBiomass}_i = \frac{\sum_{j \in MH_i^{extinct}} \widehat{\mathit{Abundance}_j} \times \mathit{BodyMass}_j}{\sum_{j \in MH_i} \widehat{\mathit{Abundance}_j} \times \mathit{BodyMass}_j}, \tag{23}$$

where $MH_i^{extinct}$ is the set of extinct megaherbivore species in region i, MH_i is the set of both extinct and extant megaherbivore species in region i, $\widehat{\mathit{Abundance}_j}$ represents the estimated number of individuals for species j, and $\mathit{BodyMass}_j$ is the average body mass of species j.[19,20]

A similar measure of lost biomass for the panel-data analysis is calculated as

$$\mathit{LostBiomass}_{i,t} = \frac{\sum_{j \in MH_{i,t}^{extinct}} \widehat{\mathit{Abundance}_j} \times \mathit{BodyMass}_j}{\sum_{j \in MH_{i,t}} \widehat{\mathit{Abundance}_j} \times \mathit{BodyMass}_j}, \tag{24}$$

where $MH_{i,t}^{extinct}$ is the set of mammals that become extinct between time t and $t-1$ in region i, and $MH_{i,t}$ is the set of mammals that are still extant at time $t-1$ in region i.

The global distribution of lost biomass due to megaherbivore extinction is depicted in Figure III. This figure also depicts regions where the independent plant cultivation occurred as reported by Larson et al. (2014). As is evident, there is large global variation in lost biomass both across and within continents. Although there are some exceptions, the figure shows visual correlation between lost biomass and the independent plant cultivation.

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[18] The predicted abundance could be sensitive to the choice of study from which the estimate is derived. Therefore, I assess the robustness of the results by using estimates from various studies. As demonstrated in the robustness section, the results remain consistent.

[19] This study focuses on wild mammals, not domesticable ones. From an individual's perspective, extinction acts as a demand-pull factor: the loss of hunting resources forces people to demand new food sources. In contrast, domesticable mammals serve as a supply-push factor, supplying more opportunities for farming and thus making it more likely. This distinction is especially important during the transition to farming, which is the main focus of this paper. For consistency in theory and empirics, I exclude the fourteen domesticable species identified by Diamond (1997) from MH_i and $MH_i^{extinct}$. However, in robustness tests, I recalculate lost biomass to include these domesticable species and show that it is positively and significantly linked to the Neolithic transition.

[20] Species extinct after the first Neolithic transition are excluded to reduce concerns of reverse causality.

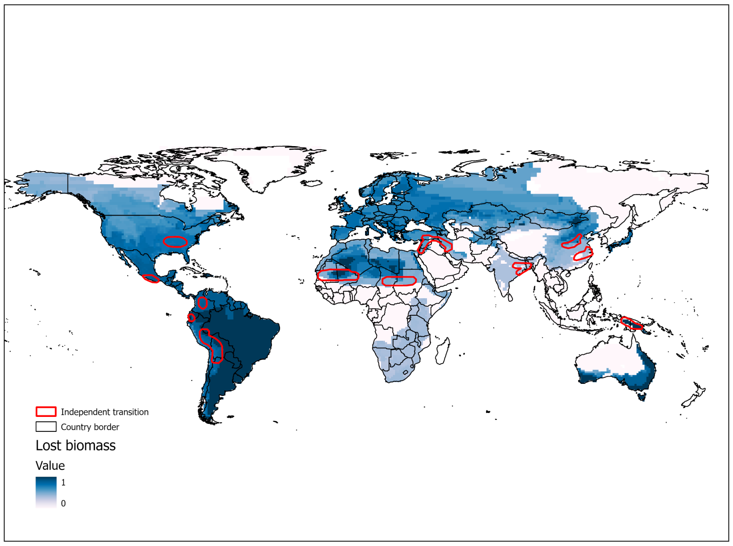

Figure III: Lost Biomass and Places of Independent Neolithic Transition

Figure IV shows the evolution of lost biomass from megaherbivore extinction in two types of regions: those with independent agricultural transitions (bold line) and those without (dashed line). The overall pattern is similar for both. Up until around 15,000 BP, neither region experienced much biomass loss. However, since then, both have seen a significant increase in lost biomass. The figure also highlights the period between the first and last independent transitions (in grey), which coincided with a severe wave of extinctions. Although the difference is not large, biomass loss was always higher in regions with independent transitions than in those without.

Unlike Riahi (2020), my measure of lost biomass offers several distinct advantages: (i) it captures both the number of species and the number of individuals within each species, (ii) it is available in both cross-sectional and panel formats across various spatial scales, and (iii) it specifically emphasizes the extinction of large herbivores.[21]

This measure of lost biomass is effective if it accurately reflects past hunting potential.

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[21] In contrast, Riahi (2020) adopts the extinction ratio measure from Sandom et al. (2014), defined as the proportion of extinct species. Thus, it does not capture the abundance of each species. His analysis focuses on large mammals, including herbivores, omnivores, and carnivores. This measure is cross-sectional and available only at very large regional scales, which are approximately equivalent to modern national boundaries.

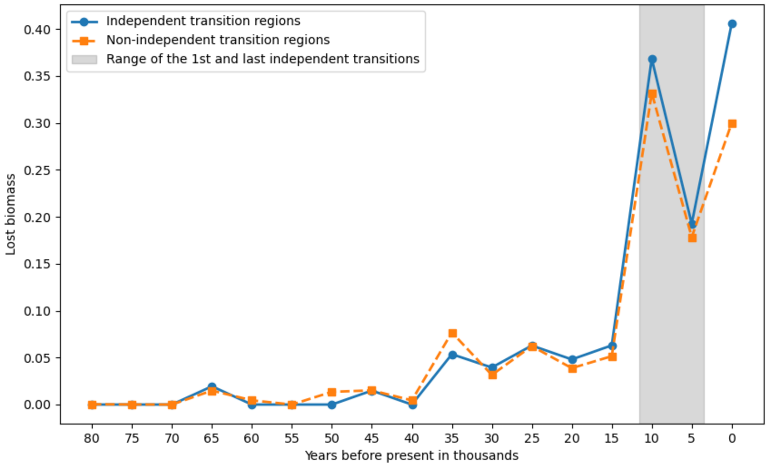

Figure IV: Evolution of Lost Biomass

Kumagai (2021) shows that megaherbivore biomass calculated in this way is a strong predictor of hunting dependency in ethnic groups, with a positive and significant association. In contrast, its relationship with other subsistence modes (gathering, fishing, husbandry, agriculture) is weak or negative, if any. Additionally, Table DIV, using the *Ethnographic Atlas*, confirms a strong negative association between lost biomass from megaherbivore extinction and hunting dependency. Thus, lost biomass is a reliable proxy for the loss of hunting resources.

3.3 Instrumental Variable: Predicted Probability of Extinction

This subsection introduces an instrumental variable for lost biomass. Several factors could produce the endogeneity of extinction. For instance, Bowles and Choi (2019) argue that some foraging settlers had private property rights, which facilitated the Neolithic Revolution. With private property rights in place, the tragedy of the commons, where prey mammals are overhunted, might have been avoided, thereby reducing biomass loss.[22] In such cases, the OLS estimate is biased downward.

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[22] The culture of foraging societies may have influenced both the agricultural transition and extinction. For example, long-term orientation could have promoted agriculture due to its need for investment (Galor and Özak, 2016), while less time spent on hunting might have mitigated mammal extinction.

The model in the theoretical section predicts that biological vulnerability increases extinction risk and influences the timing of the Neolithic transition. To construct the instrument, I use two biological traits that affect vulnerability: limb morphology and digestive systems.

Mammals can be classified based on foot posture into plantigrade and cursorial mammals. In plantigrade posture, the entire foot, from heel to toe, touches the ground, allowing walking on the whole foot. Cursorial mammals include both digitigrade and unguligrade species. Digitigrade mammals walk on their toes with the heel elevated, while unguligrade mammals walk on hooved tiptoes, with only the most distal phalanx touching the ground.

It is well known that cursorial mammals run faster and more agile than plantigrade mammals. Running speed is closely linked to limb length: longer limbs enable longer strides, allowing cursorial mammals to run faster than plantigrade mammals (Garland and Janis, 1993; Christiansen, 2002; Lovegrove, 2004). Plantigrade mammals, with their shorter limbs, are slower and more vulnerable to predation (Lovegrove, 2004).

Herbivores, which rely on plants for energy, use microbial fermentation to break down plant cellulose since vertebrates lack the enzymes to do so (Dehority, 1997). Herbivores are classified into three types based on their fermentation: hindgut fermenters, foregut non-ruminants, and foregut ruminants. Among these, ruminants are the most efficient at extracting energy from roughage, followed by foregut non-ruminants and then hindgut fermenters (Janis, 1976; Dehority, 1997; Parra, 1978; Lundgren et al., 2021).

The efficiency of the digestive system affects how much time animals spend feeding and, consequently, their exposure to hunters. Digestive efficiency depends on how long food stays in the gastrointestinal tract—longer retention allows for better fermentation and nutrient absorption. Hindgut fermenters digest food quickly, so they need to eat more frequently and spend more time feeding, which increases their risk of predation (Owen-Smith, 2002; Godoy-Vitorino et al., 2012). In contrast, foregut non-ruminants are more efficient because they retain food longer, allowing for better fermentation. However, they are still less efficient than foregut ruminants, which have specialized digestive systems that maximize energy extraction.

Foregut ruminants spend less time feeding, reducing their risk of predation, making them the most efficient herbivores at avoiding predators (Van Soest, 1996; Janis, 1976).

The *Herbitraits* database (Lundgren et al., 2021) provides information on limb morphology and digestive systems for all late Quaternary mammalian herbivores larger than 10 kg. Using this data, I developed two indices for limb and digestive inefficiency. The limb inefficiency index assigns a value of 0 if the species is cursorial and 1 if it is plantigrade. Similarly, the digestive inefficiency index assigns values of 1, 2, or 3 depending on whether the species is a foregut ruminant, foregut non-ruminant, or hindgut fermenter.

Importantly, the limb morphology and digestive systems I use in this analysis evolved long before anatomically modern humans appeared in East Africa around 300,000 years ago. Lovegrove and Haines (2004) trace the evolution of mammalian postures in Africa, showing that ancestral mammals, dating back about 100 million years, were plantigrade. Over time, some lineages evolved digitigrade limbs (around 53.8 million years ago), while unguligrade limbs developed in Perissodactyla and Cetartiodactyla around 93.2 million years ago, adaptations that persist today. Similarly, Janis (1976) outlines the evolution of digestive systems in ungulates, identifying four stages: (i) no fermentation, (ii) hindgut fermentation, (iii) foregut fermentation, and (iv) rumination. Hindgut fermentation evolved around 54 million years ago in species like horses and rhinos, while rumination appeared around 30 million years ago in species like deer and camels. These evolutionary changes predate human activity, meaning the traits I use for constructing the instrumental variable are plausibly *predetermined* by the time humans emerged.

I construct the instrument as follows. First, I regress the actual extinction status on limb inefficiency and digestive inefficiency using the *logistic* model, controlling for body mass to address potential confounding. I exclude domesticable species from the sample to avoid the concern that specific limb types and digestive systems are directly linked to domestication. Table DV shows that both limb and digestive inefficiency significantly predict extinction. Second, I calculate the predicted extinction probability using the coefficients of limb and digestive inefficiency estimated in the first step. These estimated coefficients allow the instrument to be derived from variations in exogenous biological traits.

Finally, I replace the set of extinct megaherbivores in the lost biomass measure (23) with the predicted extinction risk derived in the second step. Denoting the predicted extinction risk of species j as $\widehat{\mathbb{1}_{j \in \text{Extinct}}}$, the instrumental variable for the cross-section analysis is constructed using the following formula:

$$\widehat{LostBiomass}_i = \frac{\sum_{j \in MH_i} \widehat{\mathbb{1}_{j \in \text{Extinct}}} \times \widehat{Abundance}_j \times BodyMass_j}{\sum_{j \in MH_i} \widehat{Abundance}_j \times BodyMass_j}. \tag{25}$$

The instrument for the panel is calculated using pseudo-time variation in extinction and is constructed as follows:

$$\widehat{LostBiomass}_{i,t} = \frac{\sum_{j \in MH_{i,0}} \frac{\widehat{\mathbb{1}_{j \in \text{Extinct}}}}{\#(T)} \cdot \left[1 - \frac{\widehat{\mathbb{1}_{j \in \text{Extinct}}}}{\#(T)}\right]^{t-1} \cdot \widehat{Biomass}_j}{\sum_{j \in MH_{i,0}} \left[1 - \frac{\widehat{\mathbb{1}_{j \in \text{Extinct}}}}{\#(T)}\right]^{t-1} \cdot \widehat{Biomass}_j}, \tag{26}$$

where $\widehat{Biomass}_j$ is the product of $\widehat{Abundance}_j$ and $BodyMass_j$, and $\#(T)$ represents the number of sample periods in the panel. Thus, $\widehat{\mathbb{1}_{j \in \text{Extinct}}}/\#(T)$ and $1 - \widehat{\mathbb{1}_{j \in \text{Extinct}}}/\#(T)$ indicate the extinction risk and survival probability of species j in one period, respectively. Instead of using the set of megaherbivores in each period $MH_{i,t}$, this formula uses the initial set $MH_{i,0}$. Using $MH_{i,t}$ would be problematic because it is influenced by previous extinctions. In contrast, $MH_{i,0}$ remains unaffected by past extinctions, reducing concerns about the endogeneity of extinction.

3.4 Control Variables: Paleo-Climatic Characteristics

In this study, paleo-climatic factors are key for both identification and causality. It is widely accepted that the main drivers of mass extinction were humans and/or climate, with other factors playing little to no role (Stuart, 2015).[23] Therefore, after controlling for paleo-climate, the effect of extinction can be more confidently attributed to human activity.

Climatic factors are also considered key determinants of the agricultural transition (Dow et al., 2009; Ashraf and Michalopoulos, 2015; Matranga, 2024). Controlling for paleo-climate, thus, alleviates the concern that the observed relationship between extinction and the Neolithic transition is spurious.

To address these issues, I use the recently developed data from Beyer et al. (2020). This database provides bias-corrected, high-resolution (0.5°) global data on several climatic variables over the past 120,000 years, with a temporal resolution of 1,000-2,000 years. From this data, I calculate the means and standard deviations of paleo-temperature and paleo-precipitation. Additionally, I calculate the mean of paleo-net primary productivity, a proxy for ecosystem productivity (Rosenzweig et al., 2012), to control for potential systematic differences in ecosystems that may have influenced megaherbivore extinction and the agricultural transition.

4 Empirical Evidence

This section provides empirical evidence that megaherbivore extinction positively influenced the Neolithic Revolution. I use four complementary datasets: cross-country, cross-archaeological site, archaeological site panel, and independent transition region panel. The cross-country analysis shows a global link between extinction and the agricultural transition, though the timing of the transition is measured less precisely. Archaeological site data, while covering a smaller area than country-level data, offer more detailed information on human settlements, allowing for more accurate measurement of the Neolithic transition. Both datasets include the independent agricultural transitions and its spread, highlighting the effect of extinction on the spread of agriculture. In contrast, the independent transition re-

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[23] Recent studies increasingly support that human impact, rather than climate, was the primary cause of extinction (Sandom et al., 2014; Faurby and Svenning, 2015; Araujo et al., 2017; Andermann et al., 2020; Lemoine et al., 2023).

gion panel focuses solely on areas where farming originated independently, showing a direct link between extinction and the independent transitions. In all analyses, I control for paleoclimatic factors to better isolate human-driven extinction and address potential confounding variables.

4.1 Cross-Country Analysis

In this subsection, I present cross-country evidence of the association between the Neolithic Revolution and megaherbivore extinction. The findings show that the transition is specifically linked to megaherbivores, not small herbivores or non-herbivores (omnivores and carnivores). The analysis controls for a wide range of potentially confounding climatic and geographical factors, particularly paleo-climatic characteristics. To address concerns about endogeneity, 2SLS estimates are used, with the instrument constructed from biological vulnerability. Summary statistics are reported in Table DI.

The effect of megaherbivore extinction on the timing of the Neolithic transition is estimated using the following specification:

$$YST_i = \alpha_0 + \alpha_1 LostBiomass_i + PaleoClim_i \beta^{'} + Geo_i \gamma^{'} + Continent_i \delta^{'} + \epsilon_i, \tag{27}$$

where YST_i represents the time elapsed since the Neolithic transition in country i, $LostBiomass_i$ is the loss of biomass due to extinction in country i, $PaleoClim_i$ is a vector of paleoclimatic controls, Geo_i is a vector of geographical controls, $Continent_i$ includes continent fixed effects, and ϵ_i is the error term. The theory predicts a positive effect of lost biomass on the time since the agricultural transition, meaning $\alpha_1 > 0$.

I begin by emphasizing the unique role of megaherbivores in promoting the agricultural transition. Table I shows that megaherbivore extinction is significantly and positively associated with the timing of the transition. In contrast, the extinction of small herbivores and non-herbivores shows no meaningful connection to the transition.[24] In the horse-race model with continent fixed effects (column 7), megaherbivore extinction remains positively and significantly associated with the timing of the transition. Small herbivore extinction is not significant, while non-herbivore extinction is significant, with a negative sign. This underscores the key role of megaherbivore extinction, rather than that of small herbivores or non-herbivores.

Table I: The Neolithic Revolution and Extinction (Mutually-Disjoint Sets)

	Years elapsed since the Neolithic Revolution						
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS
Lost biomass (herbivore > 44 kg)	0.156**			0.430***			0.412***
	(0.071)			(0.100)			(0.106)
Lost biomass (herbivore <= 44 kg)		-0.150***			-0.017		0.077
		(0.031)			(0.053)		(0.060)
Lost biomass (non-herbivore)			-0.395***			-0.296***	-0.530***
			(0.116)			(0.040)	(0.178)
Continent FE				✓	✓	✓	✓
Outcome mean	49.058	49.058	49.058	49.058	49.058	49.058	49.058
Outcome std.	23.597	23.597	23.597	23.597	23.597	23.597	23.597
Adjusted R^2	0.020	0.022	0.011	0.661	0.591	0.600	0.668
Observations	147	147	147	147	147	147	147

Note: The unit of analysis is a country. Herbivores larger than 44 kg are classified as megaherbivores, while those smaller than 44 kg are classified as small herbivores. Non-herbivores consist of omnivores and carnivores. Continent fixed effects include Africa, the Americas, Asia, Europe, and Oceania. All variables are standardized. Robust standard errors are in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

Next, I examine the relationship between transition timing and megaherbivore extinction in more detail. Table II confirms a positive link between these variables. Columns 1 and 2 show a strong positive relationship using bivariate regression and regression with continent fixed effects, respectively. Columns 3 and 4 sequentially control for the means and standard deviations of paleo-temperature and paleo-precipitation, while Column 5 also includes

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[24] These categories are mutually exclusive sets of all mammals.

paleo-net primary productivity. Notably, adding these controls does not change the estimated coefficient, which remains highly significant. In Column 6, I control for the distance to the nearest agricultural origin and migratory distance from Addis Ababa. The former addresses the diffusion process from neighboring regions, while the latter accounts for prehistoric interactions between mammals and humans.[25] Column 7 adds additional geographical controls—absolute latitude, caloric suitability, terrain ruggedness, island dummy, area, and the distance to the nearest waterway. These controls also leave the estimated coefficient unchanged. Finally, Column 8 presents the 2SLS estimate, which is positive, highly significant, and supported by a strong first-stage F-statistic. The 2SLS estimate suggests that a one percentage point increase in lost biomass is associated with the agricultural transition occurring approximately 58 years earlier.

4.1.1 Robustness

Estimates from Other Studies: The primary measure of lost biomass, (23), is based on the estimate from Silva and Downing (1995). One might suspect that the results are driven by this specific study. To address this, I reconstruct the lost biomass measure using estimates from other studies. Table DVI demonstrates that the results remain robust when using these different estimates.

Recalculated Lost Biomass Including 14 Domesticable Mammals: Table DVII presents the results using recalculated lost biomass, now including the 14 domesticable mammal species. The table shows that lost biomass is strongly associated with the transition timing.

Domesticable Animals, Plants, and Extinction Rate: The presence of domesticable mammals and plants facilitated an earlier transition to agriculture (Diamond, 1997; Olsson and Hibbs Jr, 2005). Riahi (2020) suggests that large mammal extinction has a hump-

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[25] The length of mammal and human coevolution may have influenced mammals' ability to learn to avoid humans, affecting their likelihood of extinction. Similarly, humans with a longer history in an area may have been more likely to develop agriculture due to greater knowledge of the local environment.

Table II: The Neolithic Revolution and Megaherbivore Extinction

	Years elapsed since the Neolithic Revolution							
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) 2SLS
Lost biomass	0.153**	0.385***	0.404***	0.431***	0.423***	0.273***	0.309***	1.014***
	(0.074)	(0.100)	(0.094)	(0.102)	(0.098)	(0.076)	(0.098)	(0.186)
Paleo-temperature (mean)			0.384***	0.580***	0.594***	0.469***	0.482***	0.367**
			(0.075)	(0.091)	(0.086)	(0.079)	(0.119)	(0.163)
Paleo-precipitation (mean)			-0.211***	-0.101	0.027	0.066	0.079	0.269*
			(0.064)	(0.079)	(0.111)	(0.084)	(0.086)	(0.143)
Paleo-temperature (std.)				0.241***	0.226***	0.188***	0.185***	0.196***
				(0.054)	(0.055)	(0.050)	(0.062)	(0.073)
Paleo-precipitation (std.)				-0.177**	-0.184***	-0.106	-0.116*	-0.290***
				(0.073)	(0.070)	(0.066)	(0.068)	(0.085)
Paleo-net primary productivity					-0.174	-0.206**	-0.122	-0.183
					(0.111)	(0.092)	(0.126)	(0.159)
Dist. to the closest agr. origin						-0.265***	-0.229***	-0.035
						(0.051)	(0.051)	(0.084)
Migratory dist. from Addis Ababa						-0.398**	-0.405***	-0.496**
						(0.154)	(0.153)	(0.209)
Continent FE		✓	✓	✓	✓	✓	✓	✓
Additional geographic controls							✓	✓
Outcome mean	49.450	49.450	49.450	49.450	49.450	49.450	49.450	49.450
Outcome std.	23.617	23.617	23.617	23.617	23.617	23.617	23.617	23.617
First stage F								39.311
Adjusted R^2	0.018	0.669	0.736	0.765	0.767	0.847	0.852	
Observations	140	140	140	140	140	140	140	140

Note: The unit of analysis is a country. Continent fixed effects include Africa, the Americas, Asia, Europe, and Oceania. Additional geographic controls include absolute latitude, mean caloric suitability, terrain ruggedness, island dummy, area, and the distance to the closest waterway. All variables are standardized. Robust standard errors are in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

shaped relationship with the pristine agricultural transition. Table DVIII demonstrates the robustness of the results when controlling for these variables.[26]

Intermonthly Temperatuer Volatility and Climatic Seasonality: Ashraf and Michalopoulos (2015) and Matranga (2024) find that intermonthly temperature volatility and climatic seasonality influenced the transition to agriculture, respectively. Table DIX demonstrates the robustness of the results when controlling for these climate factors.[27]

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[26] The OLS estimates for lost biomass, domesticable animals, and plants are all insignificant, but the estimate for lost biomass becomes highly significant in the 2SLS analysis.

[27] The OLS estimate for lost biomass is insignificant when controlling for intermonthly temperature volatility and its square term, but it becomes highly significant in the 2SLS analysis.

Spatial Correlation: The basic result is robust to standard errors using the spatial correlation proposed by Conley (1999), as shown in Tables DX.

4.2 Archaeological Site Panel Analysis

This subsection explores the impact of lost biomass on the timing of the Neolithic Revolution, using panel data from archaeological sites based on the datasets of Pinhasi et al. (2005) and Cobo et al. (2019). I first create a grid of 1-degree by 1-degree cells and assign each archaeological site to a cell. Then, I calculate the transition timing for each grid cell by averaging the timings of the sites within it. Figure CIV presents the resulting grid map. This map is used to build a panel dataset that includes information on lost biomass and paleo-climate.[28] Summary statistics are provided in Table DII.

The effect of lost biomass on the timing of the Neolithic transition is estimated by:

$$\mathbb{1}_{i,t} = \alpha_0 + \alpha_1 LostBiomass_{i,t-1} + PaleoClim_{i,t-1}\beta^{'} + Cell_i\gamma^{'} + Time_t\delta^{'} + \epsilon_{i,t}, \tag{28}$$

where $\mathbb{1}_{i,t}$ is a dummy variable that indicates whether agricultural transition occurs in cell i at period t, $LostBiomass_{i,t-1}$ is loss of biomass caused by megaherbivore extinction in cell i in period $t-1$, $PaleoClim_{i,t-1}$ is a vector of paleo-climatic variables, including paleo-net primary productivity, for cell i in period $t-1$, $Cell_i$ is cell fixed effects, $Time_t$ is time fixed effects, and $\epsilon_{i,t}$ is an error term. The Neolithic transition dummy variable, $\mathbb{1}_{i,t}$, takes the value of 0 for all periods before the transition occurs. Once a unit in the dataset undergoes the agricultural transition, it is dropped from the panel, as further transitions are no longer possible. The analysis period spans from 21,000 BP until the transition occurs, with each time window representing 1,000 years.[29]

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[28] To save space, I present the cross-archaeological site analysis results in the appendix. Table DXI shows a strong relationship between lost biomass and transition timing, using data from 1-degree by 1-degree grid cells.

[29] Paleo-climate data from Beyer et al. (2020) is available in 1,000-year intervals from 21,000 BP onward. For earlier periods, data is only available in 2,000-year intervals.

Table III: Basic Result and Placebo Test (Archaeological Site Panel)

	The NR indicator							
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS
Lost biomass (t-1)	0.110*** (0.020)	0.105*** (0.019)	0.106*** (0.019)	0.103*** (0.020)				
Lost biomass (t+1)					-0.000 (0.018)	-0.009 (0.018)	-0.011 (0.018)	-0.011 (0.018)
Paleo-temperature (mean) (t-1)		0.282*** (0.075)	0.381*** (0.081)	0.605*** (0.085)		0.322*** (0.078)	0.431*** (0.083)	0.655*** (0.087)
Paleo-precipitation (mean) (t-1)		-0.578*** (0.060)	-0.612*** (0.063)	-0.370*** (0.070)		-0.567*** (0.061)	-0.601*** (0.063)	-0.358*** (0.071)
Paleo-temperature (std.) (t-1)			0.166** (0.074)	0.070 (0.074)			0.187*** (0.071)	0.090 (0.073)
Paleo-precipitation (std.) (t-1)			0.125*** (0.048)	0.076 (0.048)			0.124** (0.049)	0.075 (0.049)
Paleo-net primary productivity (t-1)				-0.488*** (0.069)				-0.491*** (0.069)
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓
Outcome mean	0.060	0.060	0.060	0.060	0.059	0.059	0.059	0.059
Outcome std.	0.237	0.237	0.237	0.237	0.235	0.235	0.235	0.235
Adjusted R-Sqr.	0.299	0.313	0.314	0.321	0.289	0.304	0.305	0.312
Observations	8356	8356	8356	8356	8341	8341	8341	8341

Note: The unit of analysis is a 1° × 1° grid cell. The dependent variable is a dummy that equals 1 if a grid cell undergoes an agricultural transition and 0 otherwise. The panel spans from 21,000 BP until the transition occurs, using 1,000-year time windows. All variables are standardized. Robust standard errors, clustered at the grid cell level, are reported in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.10$.

Columns 1-4 of Table III presents a strong positive relationship between the Neolithic transition and lost biomass. All columns report OLS estimates, including both cell and time fixed effects. The estimated coefficient for lost biomass remains highly robust, even when controlling for the means of paleo-temperature and paleo-precipitation (column 2), their standard deviations (column 3), and paleo-net primary productivity (column 4). By controlling for paleo-climatic characteristics, the estimated coefficient of lost biomass is better interpreted as human-driven and causal.

This is a particularly demanding specification because lost biomass equals 0 for most observations. Out of 8,356 observations, which result from the combination of cells and periods, approximately 95% show a value of 0 for lost biomass (Figure CV). Similarly, the Neolithic transition indicator exhibits limited variation, with around 94% of observations (cells × periods) taking a value of 0. As a result, controlling for both cell and time fixed effects, along with paleo-climatic variables, absorbs much of the variation in the data. Nevertheless, lost biomass continues to exhibit a highly significant and positive effect on the likelihood of an agricultural transition.

Next, I replace the one-period lagged lost biomass with one-period ahead lost biomass in equation (28). Columns 5-8 of Table III presents the results of this placebo test. Reassuringly, the estimates are insignificant across all specifications, with magnitudes very close to 0. This placebo test provides additional evidence supporting the effect of lost biomass on the agricultural transition.

Then, I perform an instrumental variable analysis. Table IV shows the results of the 2SLS analysis. The estimates from the second stage (Panel A), first stage (Panel B), and reduced form (Panel C) are all statistically significant at the 1% level and remain consistent across various specifications. The results indicate that a one percentage point increase in lost biomass raises the probability of the Neolithic transition by approximately 9.2 percentage point. These findings, based on exogenous variation in extinction and controlling for paleo-climatic factors along with cell and time fixed effects, provide strong evidence that megaherbivore extinction significantly influenced the likelihood of the Neolithic Revolution.

4.2.1 Robustness

Estimates from Other Studies: The primary measure of lost biomass, (24), is based on the estimate from Silva and Downing (1995). One might suspect that the results are driven by this specific study. To address this, I reconstruct the lost biomass measure using estimates from other studies. Table DXII demonstrates that the results remain robust when using these different estimates.

Table IV: 2SLS, First Stage, and Reduced Form (Archaeological Site Panel)

	Panel A: second-stage The NR indicator				**Panel B**: first-stage Lost biomass (t-1)				**Panel C**: reduced form The NR indicator			
	(1) 2SLS	(2) 2SLS	(3) 2SLS	(4) 2SLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS	(9) OLS	(10) OLS	(11) OLS	(12) OLS
Lost biomass (t-1)	3.492***	3.433***	3.409***	3.566***								
	(0.701)	(0.813)	(0.806)	(0.796)								
Lost biomass (IV) (t-1)					2.405***	2.169***	2.218***	2.371***	8.398***	7.447***	7.561***	8.457***
					(0.494)	(0.514)	(0.523)	(0.539)	(1.325)	(1.306)	(1.302)	(1.262)
Paleo-temperature (mean) (t-1)		-0.547*	-0.349	-0.279		0.223***	0.192***	0.236***		0.218**	0.306***	0.561***
		(0.281)	(0.282)	(0.316)		(0.046)	(0.050)	(0.053)		(0.085)	(0.092)	(0.098)
Paleo-precipitation (mean) (t-1)		-0.802***	-0.825***	-0.718***		0.069**	0.065*	0.117**		-0.564***	-0.605***	-0.302***
		(0.129)	(0.139)	(0.176)		(0.034)	(0.037)	(0.045)		(0.071)	(0.074)	(0.083)
Paleo-temperature (std.) (t-1)			0.397**	0.360**			-0.080	-0.102*			0.124	-0.004
			(0.168)	(0.178)			(0.050)	(0.053)			(0.083)	(0.084)
Paleo-precipitation (std.) (t-1)			0.071	0.045			0.027	0.017			0.161***	0.107**
			(0.107)	(0.113)			(0.035)	(0.036)			(0.054)	(0.052)
Paleo-net primary productivity (t-1)				-0.232				-0.101***				-0.593***
				(0.146)				(0.037)				(0.073)
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Outcome mean	0.063	0.063	0.063	0.063	0.020	0.020	0.020	0.020	0.063	0.063	0.063	0.063
Outcome std.	0.244	0.244	0.244	0.244	0.095	0.095	0.095	0.095	0.244	0.244	0.244	0.244
First stage F	23.737	17.802	17.971	19.353								
Adjusted R-Sqr.					0.267	0.268	0.269	0.269	0.306	0.317	0.318	0.327
Observations	7850	7850	7850	7850	7850	7850	7850	7850	7850	7850	7850	7850

Note: The unit of analysis is a 1° × 1° grid cell. The dependent variable is a dummy that equals 1 if a grid cell undergoes an agricultural transition and 0 otherwise. The panel spans from 21,000 BP until the transition occurs, using 1,000-year time windows. All variables are standardized. Robust standard errors, clustered at the grid cell level, are reported in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.10$.

Recalculated Lost Biomass Including 14 Domesticable Mammals: Table DXIII presents the results using recalculated lost biomass, now including the 14 domesticable mammal species. The table shows that lagged lost biomass is strongly associated with the transition dummy, while one-period ahead lost biomass is consistently insignificant.

Intermonthly Temperature Volatility and Climatic Seasonality: Ashraf and Michalopoulos (2015) and Matranga (2024) find that intermonthly temperature volatility and climatic seasonality influenced the transition to agriculture, respectively. Table DXIV demonstrates the robustness of the results when controlling for these climate factors.

Spatial Correlation: Table DXV shows that the results remain robust after correcting for spatial correlation. The findings hold when clustering standard errors at x-degree by x-degree neighboring grid cells ($x = 1.5, 2, 2.5$) and when applying the spatial correlation technique proposed by Conley (1999).

4.3 Independent Transition Grid Cell Panel Analysis

This subsection examines the impact of lost biomass on independent agricultural transitions using 1° × 1° grid cell panel data. Larson et al. (2014) identify the well-established locations of independent plant domestication (Figure CIII). First, I divide the earth into 1° × 1° grid cells and overlay these cells on the map of independent domestication sites. I then assign the year of transition to grid cells that overlap with domestication regions. Figure CVI shows the resulting map, where darker colors represent earlier transitions, and white indicates no independent transition. Using this map, I construct the grid cell panel data. The relationship between lost biomass and independent agricultural transitions is estimated using equation (28). Since the analysis focuses solely on independent transitions, the estimated coefficient of lost biomass reflects its effect on independent transitions, not on the diffusion of agriculture. Summary statistics is found in Table DIII

Columns 1-4 of Table V presents a strong positive relationship between the independent transition and lost biomass. All columns report OLS estimates, including both cell and time fixed effects. The estimated coefficient for lost biomass remains highly robust, even when controlling for the means of paleo-temperature and paleo-precipitation (column 2), their standard deviations (column 3), and paleo-net primary productivity (column 4). By controlling for paleo-climatic characteristics, the estimated coefficient of lost biomass is better interpreted as human-driven and causal.

This is a particularly demanding specification because lost biomass equals 0 for most observations. Out of 33,827 observations, which result from the combination of cells and periods, approximately 90% show a value of 0 for lost biomass (Figure CVII). Similarly, the independent transition indicator exhibits limited variation, with around 99.8% of observations (cells × periods) taking a value of 0. As a result, controlling for both cell and time fixed effects, along with paleo-climatic variables, absorbs much of the variation in the data.

Table V: Basic Result and Placebo Test (Independent Transition)

	The independent NR indicator							
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS
Lost biomass (t-1)	0.015***	0.016***	0.016***	0.016***				
	(0.004)	(0.004)	(0.004)	(0.004)				
Lost biomass (t+1)					-0.019***	-0.019***	-0.019***	-0.019***
					(0.002)	(0.002)	(0.002)	(0.002)
Paleo-temperature (mean) (t-1)		-0.292***	-0.281***	-0.284***		-0.295***	-0.283***	-0.287***
		(0.016)	(0.016)	(0.016)		(0.016)	(0.016)	(0.016)
Paleo-precipitation (mean) (t-1)		0.054***	0.046**	0.023		0.046**	0.036*	0.015
		(0.020)	(0.020)	(0.019)		(0.021)	(0.021)	(0.020)
Paleo-temperature (std.) (t-1)			0.028***	0.031***			0.031***	0.034***
			(0.004)	(0.004)			(0.004)	(0.004)
Paleo-precipitation (std.) (t-1)			0.029***	0.036***			0.030***	0.037***
			(0.010)	(0.010)			(0.010)	(0.011)
Paleo-net primary productivity (t-1)				0.043***				0.041**
				(0.016)				(0.017)
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓
Outcome mean	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Outcome std.	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
Adjusted R-Sqr.	0.027	0.028	0.028	0.028	0.024	0.025	0.025	0.025
Observations	338827	338827	338827	338827	321984	321984	321984	321984

Note: The unit of analysis is a 1° × 1° grid cell. The dependent variable is a dummy that equals 1 if a grid cell undergoes an independent agricultural transition and 0 otherwise. The panel spans from 21,000 BP until the transition occurs, using 1,000-year time windows. All variables are standardized. Robust standard errors, clustered at the grid cell level, are reported in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.10$.

Nevertheless, lost biomass continues to exhibit a highly significant and positive effect on the likelihood of an independent agricultural transition.

Next, I replace the one-period lagged lost biomass with one-period ahead lost biomass in equation (28). Columns 5-8 of Table V presents the results of this placebo test, which shows significant relationship between the independent transition and one-period ahead lost biomass. However, this association is always negative, which is inconsistent with the proposed hypothesis.

Then, I perform an instrumental variable analysis. Table VI shows the results of the

Table VI: 2SLS, First Stage, and Reduced Form (Independent Transition)

	Panel A: second-stage The independent NR indicator				**Panel B**: first-stage Lost biomass (t-1)				**Panel C**: reduced form The independent NR indicator			
	(1) 2SLS	(2) 2SLS	(3) 2SLS	(4) 2SLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS	(9) OLS	(10) OLS	(11) OLS	(12) OLS
Lost biomass (t-1)	0.794***	0.693***	0.690***	0.691***								
	(0.155)	(0.143)	(0.135)	(0.136)								
Lost biomass (IV) (t-1)					1.735***	1.786***	1.898***	1.882***	1.378***	1.237***	1.311***	1.300***
					(0.215)	(0.211)	(0.213)	(0.211)	(0.230)	(0.229)	(0.230)	(0.229)
Paleo-temperature (mean) (t-1)		-0.481***	-0.487***	-0.487***		0.273***	0.303***	0.296***		-0.291***	-0.278***	-0.282***
		(0.046)	(0.048)	(0.047)		(0.013)	(0.014)	(0.014)		(0.016)	(0.016)	(0.016)
Paleo-precipitation (mean) (t-1)		0.215***	0.212***	0.215***		-0.234***	-0.243***	-0.282***		0.053***	0.044**	0.020
		(0.041)	(0.041)	(0.044)		(0.013)	(0.013)	(0.016)		(0.020)	(0.020)	(0.020)
Paleo-temperature (std.) (t-1)			-0.018	-0.018			0.074***	0.079***			0.033***	0.036***
			(0.012)	(0.012)			(0.010)	(0.010)			(0.004)	(0.004)
Paleo-precipitation (std.) (t-1)			0.028***	0.027**			0.004	0.017**			0.031***	0.039***
			(0.011)	(0.012)			(0.008)	(0.008)			(0.010)	(0.011)
Paleo-net primary productivity (t-1)				-0.006				0.074***				0.046***
				(0.019)				(0.013)				(0.016)
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Outcome mean	0.002	0.002	0.002	0.002	0.037	0.037	0.037	0.037	0.002	0.002	0.002	0.002
Outcome std.	0.046	0.046	0.046	0.046	0.144	0.144	0.144	0.144	0.046	0.046	0.046	0.046
First stage F	65.320	71.455	79.085	79.194								
Adjusted R-Sqr.					0.208	0.210	0.210	0.210	0.029	0.030	0.030	0.030
Observations	322448	322448	322448	322448	322448	322448	322448	322448	322448	322448	322448	322448

Note: The unit of analysis is a 1° × 1° grid cell. The dependent variable is a dummy that equals 1 if a grid cell undergoes an independent agricultural transition and 0 otherwise. The panel spans from 21,000 BP until the transition occurs, using 1,000-year time windows. All variables are standardized. Robust standard errors, clustered at the grid cell level, are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

2SLS analysis. The estimates from the second stage (Panel A), first stage (Panel B), and reduced form (Panel C) are all statistically significant at the 1% level and remain consistent across various specifications. The results indicate that a one percentage point increase in lost biomass raises the probability of the independent transition by approximately 0.29 percentage point. This finding, based on exogenous variation in extinction and controlling for paleo-climatic factors along with cell and time fixed effects, provides strong evidence of the impact of megaherbivore extinction on the likelihood of the independent agricultural transition.

4.3.1 Robustness

Estimates from Other Studies: The primary measure of lost biomass, (24), is based on the estimate from Silva and Downing (1995). One might suspect that the results are driven by this specific study. To address this, I reconstruct the lost biomass measure using estimates from other studies. Table DXVI demonstrates that the results remain robust when using these different estimates.

Recalculated Lost Biomass Including 14 Domesticable Mammals: Table DXVII presents the results using recalculated lost biomass, now including the 14 domesticable mammal species. The table shows that lagged lost biomass is strongly positively associated with the transition dummy, while one-period ahead lost biomass is always negative.

Intermonthly Temperatuer Volatility and Climatic Seasonality: Ashraf and Michalopoulos (2015) and Matranga (2024) find that intermonthly temperature volatility and climatic seasonality influenced the transition to agriculture, respectively. Table DXVIII demonstrates the robustness of the results when controlling for these climate factors.

Spatial Correlation: Table DXIX shows that the results remain robust after correcting for spatial correlation. The findings hold when clustering standard errors at x-degree by x-degree neighboring grid cells ($x = 1.5, 2, 2.5$) and when applying the spatial correlation technique proposed by Conley (1999).

5 Concluding Remarks

The Neolithic Revolution was a major transformation in humanity that has shaped the wealth of nations through its influence on institutions and culture. Understanding the reasons behind this transition is one of the most important questions in prehistory and is key to understanding the world today.

This research explores the impact of large-herbivore extinction on the Neolithic Revolution, both theoretically and empirically. It uses new datasets on mammal species to measure the loss of hunting opportunities caused by extinction. The research, which uses complementary datasets, controls for paleo-climatic factors, and applies an instrumental variable approach, shows a significant and robust impact of the extinction of large herbivores on the emergence and diffusion of agriculture.

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Online Appendix for “Overkill, Extinction, and the Neolithic Revolution” (Not for Publication)

Motohiro Kumagai

Appendix A

In this section, I summarize the historical records of large-herbivore extinction and the independent adoption of agriculture in the following regions: the Levant, the Andes, North China, South-Central China, Mesoamerica, Eastern North America, and the Sahel. This follows the approach of Matranga (2024), who used these seven regions to examine the relationship between climatic seasonality and the emergence of agriculture.

The Levant

The Levant is the best-known region that experienced the earliest transition to agriculture. This region is generally characterized by biogeographically, geographically, and climatically suitable conditions for agriculture. Some sites contain incontestable evidence of a set of domesticated crops and animals including barley, emmer wheat, einkorn wheat, flax, lentils, peas, goats, sheep, cattle, and pigs during the Pre-Pottery Neolithic B (PPNB; ca. 10,450-8,950 BP). Moreover, domesticated characteristics were already present in a few sites by 10,450 BP. Therefore, by 10,950-9,250 BP, domesticated crops had attained dominant roles in human subsistence within the Levant (Asouti and Fuller (2012); Bellwood (2006)).

The Levant experienced the shift from large to small animals in prehistoric times because of an overall increase in hunting of large mammals. Before the Pre-Pottery Neolithic A (PPNA; ca. 11,450-10,450 BP), people primarily depended on large species such as equids and aurochs. However, these mammals became rare and in some cases extinct because of intensive hunting. As a result, in the PPNA people were dependent upon small animals such as birds and fish (Davis et al., 1988). Some large herbivores disappeared from this region in the Late Pleistocene. In several areas in northern and central Israel—such as Mount Carmel, Ein Gev, and Fazael—there was a marked decrease in the number of, or even disappearance of, a deer species including some gazelle around 12-10,000 BP (Davis, 1982). Another example of extinction in this period is *Equus hydruntinus*, which survived until around 12,000 BP in northern Israel (Davis, 1980). The chronology and the shift of subsistence modes in the Levant are consistent with the proposed theory.

Eastern North America

Eastern North America saw independent domestication of several plants. Radiocarbon and archaeobotanical evidence show that the following plants were cultivated: marshelder (*Iva annua*), chenopod (*Chenopodium berlandieri*), squash (*Cucurbita pepo*), sunflower (*Helianthus annuus*), and bottle gourd (*Lagenaria siceraria*) (Smith and Yarnell, 2009). Genetic and archaeological evidence, in particular, suggest that marshelder, chenopod, squash, and sunflower were independently domesticated and that they had been domesticated by approximately 4,400, 3,700, 5,000, and 4,800 BP, respectively.

The Americas are the main regions subject to Paul Martin's overkill hypothesis, according to which humans were the cause of megafauna extinction in the Pleistocene (Martin, 1967; Mosimann and Martin, 1975; Martin and Klein, 1984). The initial colonization of North America by humans occurred about 15,000-13,000 BP (Braje and Erlandson, 2013; Stuart, 2015; Smith et al., 2018). Megafauna abruptly became extinct, and North America lost approximately three genera of elephants, six of giant edentates, fifteen of ungulates, and various giant rodents and carnivores. These extinctions between 11,450 and 10,450 BP coincide with the age of the Clovis foragers, who depended on large animal hunting as a subsistence mode (Davis, 2012). In eastern North America, for instance, *Cervalces scotti*, *Megalonyx jeffersonii*, *Platygonus compressus*, *Mylohyus nasutus*, *Castoroides ohioensis*, and *Mammut americanum* went extinct approximately 11,405, 11,430, 11,130, 11,860, 10,850, and 10,970 BP, respectively (Fiedel, 2009).

There are not many kill sites that show that humans were responsible for these extinction, and thus whether humans caused all these extinctions is disputable. However, the eastern North America case provides consistent chronology of extinction of large herbivore, plant cultivation, domestication and agriculture.

Mesoamerica

Maize (*Zea mays L.*) and squash (*Cucurbita spp.*) were the first crops to be domesticated in Mesoamerica. Strong evidence of the domestication comes from starch grain and phytolith residues from the ground and chipped stone tools found at the Xihuatoxtla Shelter in southwestern Mexico. They indicate that these crops had been domesticated by approximately 8,700 BP (Ranere et al., 2009).[30] Paleoecological and archaeological records also show evidence of agricultural intensification after this period. Between 7,000 and 5,550 BP, levels of the Asteraceae family of weeds increased, maize-pollen accumulation increased, and carbon deposits decreased. During a similar time period, new tool kits began to appear, such as levers, bifacial knives, and grinding handstones. These records indicate agriculture intensified during this period (Zizumbo-Villarreal and Colunga-GarcíaMarín, 2010).

Human skeletal remains found in caves near Tulum in Mexico indicate that humans were present in Mesoamerica as long ago as 13,000 BP (Stinnesbeck et al., 2017). There are many mammoth localities in Mexico, and some indicate mammoth-human relationships. Mammoth skeletons found at Santa Isabel Iztapa date to about 9,000 BP and earlier, and the skeletons had possible cut marks on the epiphyses and articulating facets of the long bones. Likewise, a tusk and a mandible found at La Villa de Guadalupe show extensive cut marks, and they have been dated to 11,320 BP (Arroyo-Cabrales et al. (2006)). El Fin del Mundo in the Mexican state of Sonora provides further evidence of the relationship between

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[30] Based on molecular clock analysis, Zizumbo-Villarreal and Colunga-GarcíaMarín (2010) argue that wild and domesticated maize populations genetically separated by c. 9000 BP. This estimate is consistent with the result by Ranere et al., 2009.

humans and large herbivores. Artifacts found in association with bones indicate that the Clovis people hunted gomphotheres (*Cuvieronius*) until c. 11,550 BP (Sanchez et al., 2014).

Mesoamerica is a good example of a sequential shift of human subsistence mode. Zizumbo-Villarreal and Colunga-GarcíaMarín (2010) argue that the Clovis people originally hunted large mammals. Because of mass extinction, they shifted to hunting small game and gathering in the dry tropical forest of the Balsal-Jalisco. Then the Clovis started plant domestication and agriculture in approximately 10,000 BP.[31]

The Andes

The history of agricultural transition in South America is not simple, and the dates of cultivation and domestication are differ a lot among species (Larson et al., 2014). Nevertheless, multifaceted archaeobotanical and artificial records indicate that the Andes is a center of pristine agriculture. In the Zaña Valley of Peru, by 8,800-7,600 BP a significant number of dietary calories and nutrients were coming from crop plants such as *Phaseolus*, *Cucurbita moschata*, peanuts, and *Inga feuillea* (Piperno, 2011). In northern and central Peru, irrigated agriculture had been practiced since the Late Preceramic Period. Subsistence depended on squash, beans, sweet potatoes, potatoes, achira, chili peppers, and avocados, and hence the region was home to large agricultural polities by 2000 BC (Bellwood, 2006).

South America was colonized by humans about 12,900-11,500 BP (Grayson and Meltzer, 2002; Barnosky et al., 2004), and there are many sites with remains of large mammals. The associations between humans and extinct megafauna are generally accepted (Koch and Barnosky, 2006). As for the Andean regions, the Quebrada Santa Julia and Cueva del Milodon in Chile are good examples of associations between artifacts and megafauna bones. For these sites, associated dates are about 10,200-11,090 BP (Fiedel, 2009). Given the available evidence, Fiedel favors the view that the Clovis people and their descendants caused the extinction of megafauna in South America. In the Andes, the chronology of human

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[31] Piperno (2011) gives a similar argument based on the region from the Central Balsas of southwest Mexico to Bolivia.

colonization, megaherbivore extinction and the beginnings of cultivation, domestication and agriculture is consistent with the proposed theory.

North and South-Central China

In northern China, early agricultural activities started focusing on millets along the Yellow River by c. 8,000 BP; by this time, domestic pigs were prevalent (Larson et al., 2010). Zhao (2011) argues that the origin of dry-land agriculture in North China should be divided into three periods. The first period is cultivation and domestication of millet starting around 10,000 BP. The second period is a transitional phase from hunting and gathering to dry-land agriculture between 9,000 and 7,000 BP. The final period is from 7,000 to 6,000 BP, when millet-farming-based subsistence agriculture was established, which is consistent with estimates by Liu et al. (2012).

In south-central China, rice was first domesticated along the Yangze River. Sedentary hunter-gatherers started rice cultivation by c. 6,000 BP, and as in North China, pigs were domesticated in this region by at least 8,000 BP (Larson et al., 2010). Zhao (2011) argues that the origin of rice agriculture should be divided into three periods. The first is rice cultivation starting about 10,000 BP. The second, between 9,000 and 6,500 BP, is a transitional period from hunting and gathering to rice agriculture. The final period runs from 6,500 to 4,500 BP, when rice-agriculture-based subsistence was established. Zhao also states that the region fully shifted to rice agriculture about 6,400-5,300 BP.

Modern humans were present in China by at least 40,000 BP, and there is archaeological evidence for human hunting of large mammals across the Late Pleistocene and Pleistocene-Holocene transition (Turvey et al., 2013). Turvey et al. (2013)'s analyses indicate that both in northern and south-central China, megafauna that had been previously thought to be Holocene survivors were likely extinct before the Holocene. For example, from the assemblage found at Gulin, in Sichuan Province, they argue that megaherbivores such as *Megatapirus augustus, Rhinoceros sinensis,* and *Stegodon orientalis* became extinct by at least 10,175 BP. Kuzmin (2010) show that ^{14}C date on the rhinoceros bone found at the Hutouliang locality is approximately 11,000 BP, and argue that this date is likely to become older.

The Sahel

Although the Sahara today is a hot desert, this has not always been the case. During the 'African Humid Period,' which began in approximately 12,000 BP, the Sahara was wetter and covered by grasses, trees, and lakes; it has been called the 'Green Sahara.' (Manning and Timpson, 2014). This humid period abruptly ended around 6,000-5,000 BP, which made the region barren and lakes dried up. The first indigenous African crop appeared in the Sahara: pearl millet (*Pennisetum glaucum*). This crop is highly adapted to drought and poor soils, growing even in dry areas such as the Sahara after the African Humid Period (Garí, 2002). Several studies show that domestication of pearl millet began at least as far back as approximately 4,500 BP (Manning et al., 2011; Fuller and Hildebrand, 2013).

The history of megafauna extinction in Africa seems different from that of other continents. Generally, Africa lost less megafauna than other continents, and it is considered 'a fortunate anomaly' (Faith (2014)). Many regions of Sub-Saharan Africa support the most diversity of terrestrial megafauna today (Faurby and Svenning, 2015). However, North Africa lost some large herbivores, although they have received the least attention. For instance, *Syncerus antiquus* and *Equus algericus* went extinct approximately 5,400 BP. When it comes to more local extinction, there are possibly more extinct megaherbivores in the Late Pleistocene and early Holocene such as *Bos primigenius* and *Equus mauritanicus* (Faith (2014)).

Due to the limited academic attention and archaeological records, it is difficult to understand megaherbivore extinction in Africa for now. However, the available evidence indicates the possibility of megaherbivore extinction in the Sahel region, followed by domestication of some plant crops.

Appendix B

Proposition 2 *Suppose that* $y^a_t < y^h_t$ *and* $y^a_d = y^h_d$ *for* $t \in [0, d-1]$*, and that* $\exists f \geq d+1$ *s.t.* $n[y^a_{f-1}] < 1 \leq n[y^a_f]$*. Then,* $\exists t^* \geq d+1$ *s.t. for* $i \in [d, t^*-1]$ *and* $m \in [0, d-1]$*,*

i. $y^a_i < y^h_m$*; and*

ii. $w^a_i > w^h_m$*.*

Proof. Notice that the assumption is enough to guarantee that an economy transits to agriculture.

Define c as the period when the economy crosses the Replacement Frontier, L^{LL}. First, I show that $\exists t^* \geq d+1$ s.t. $\forall i \in [d, t^*-1]$ and $\forall j \in [c+1, d-1]$, $y^a_i < y^h_j$. For $j \in [c+1, d-1]$, the economy is below the Hunting-Farming Frontier, L^{yy}. Thus, $L^h_j < (A^h/A^a_j X^a)B_j$. Since $y^a_d = y^h_d$, individuals are indifferent between hunting and farming, and some individuals start cultivation at the period d. Due to learning by doing, (5), it must be: $A^a_0 = A^a_a = ... = A^a_d < A^a_{d+1} < ....$ Therefore, there exists $t^* \geq d+1$ s.t. for $j \in [c+1, d-1]$, $L^h_j < (A^h/A^a_{t^*-1}X^a)^{1/\alpha}B_j$ and $L^h_j \geq (A^h/A^a_{t^*}X^a)^{1/\alpha}B_j$. From (2) and (4), $y^a_i < y^h_j$.

Then, I show that for this t^*, $y^a_i < y^h_k$ $\forall i \in [d, t^*-1]$ and $\forall k \in [0, c]$. For $k \in [0, c]$, the economy is below or on L^{LL} and for $j \in [c+1, d-1]$, it is above L^{LL}_j. Thus, $n[y^h_j] < 1 \leq n[y^h_k]$. From (11) and (12), $y^h_j < y^h_k$. Since $y^a_i < y^a_j$, we have $y^a_i < y^h_k$ for $i \in [d, t^*-1]$.

Therefore, I showed: $\exists t^* \geq d+1$ s.t. $\forall i \in [d, t^*-1]$ and $\forall m \in [0, d-1]$, $y^a_i < y^h_m$. As shown in (11), $\partial w^*_t / \partial y_t < 0$. Thus, $w^a_i > w^h_m$. ■

Appendix C

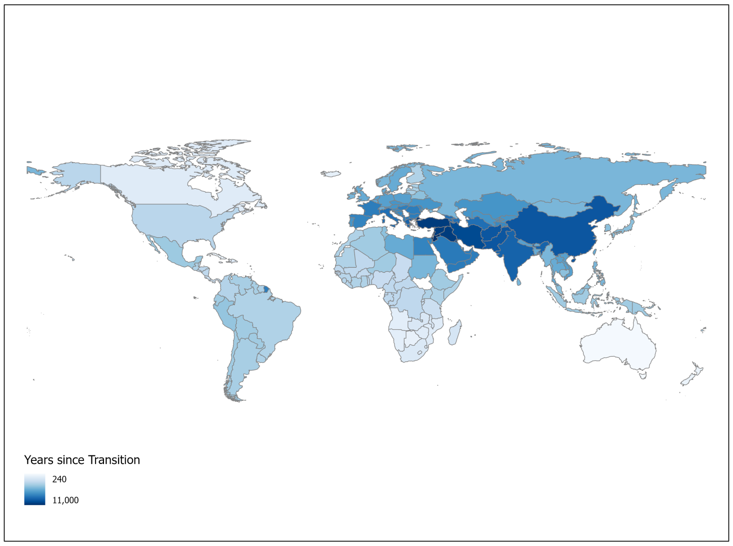

Figure CI: Years Elapsed since the Neolithic Revolution (Borcan et al., 2018)

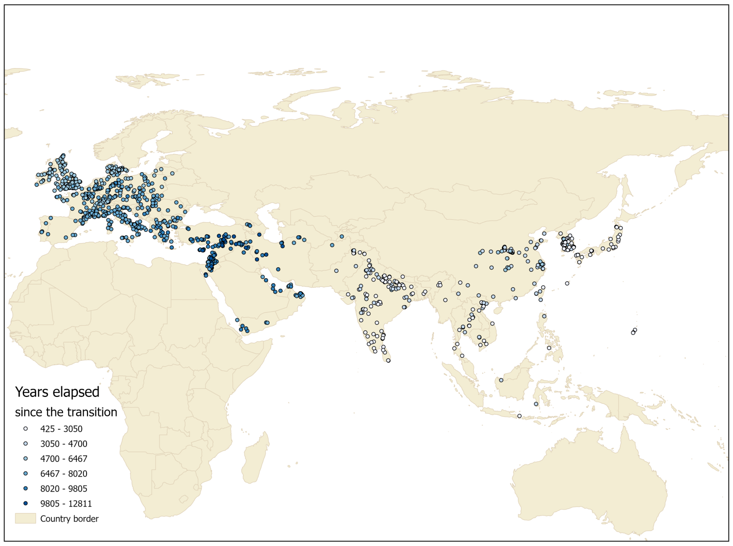

Figure CII: Years Elapsed since the Neolithic Revolution (Pinhasi et al., 2005; Cobo et al., 2019)

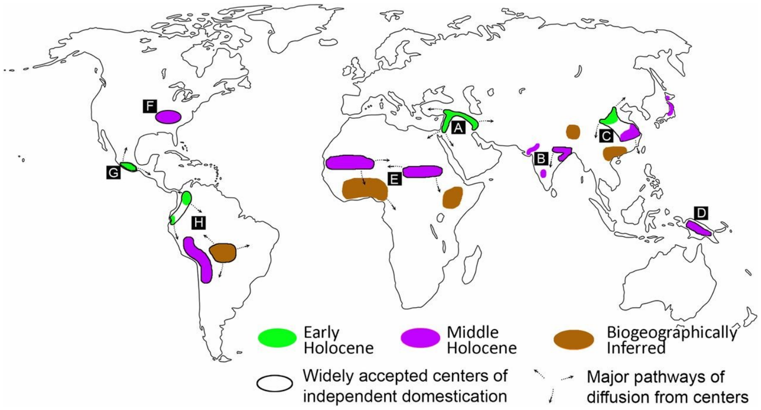

Figure CIII: Places of the Independent Agricultural Transition (Larson et al., 2014)

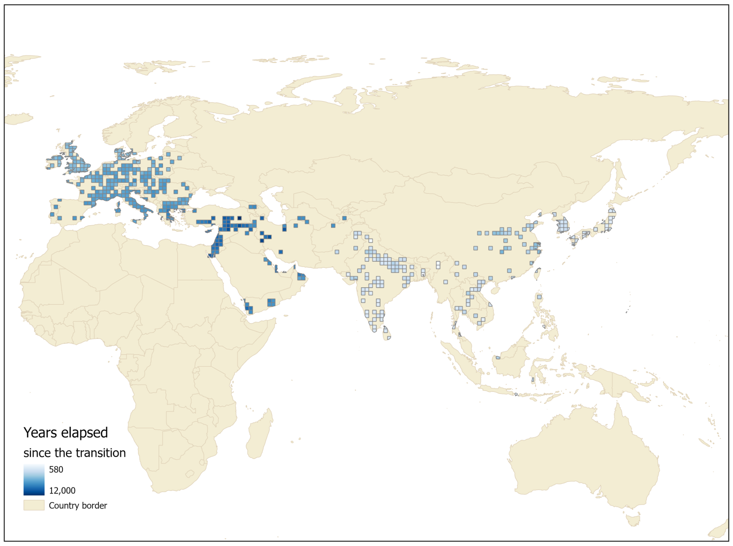

Figure CIV: Years Elapsed since the Neolithic Revolution at the 1° × 1° Grid Cell Level (Pinhasi et al., 2005; Cobo et al., 2019)

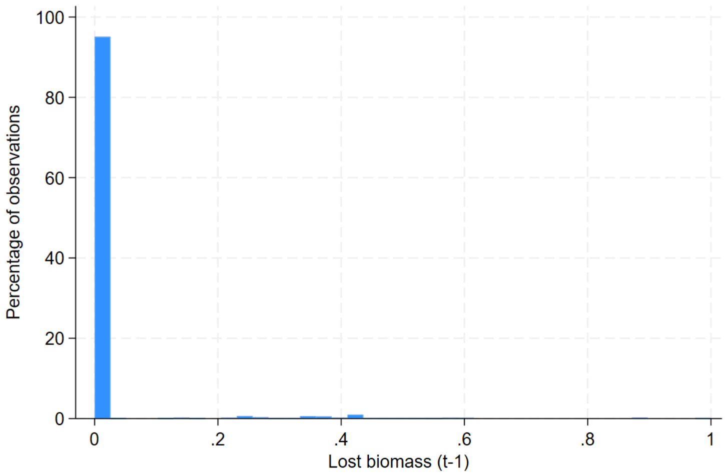

Figure CV: Histogram of Lost Biomass (Archaeological Site Panel)

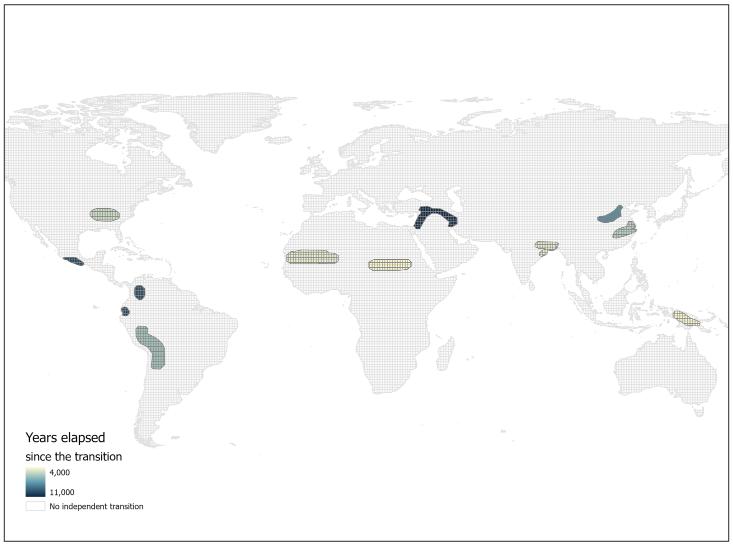

Figure CVI: 1-Degree by 1-Degree Grid Cell with the Independent Transition Places

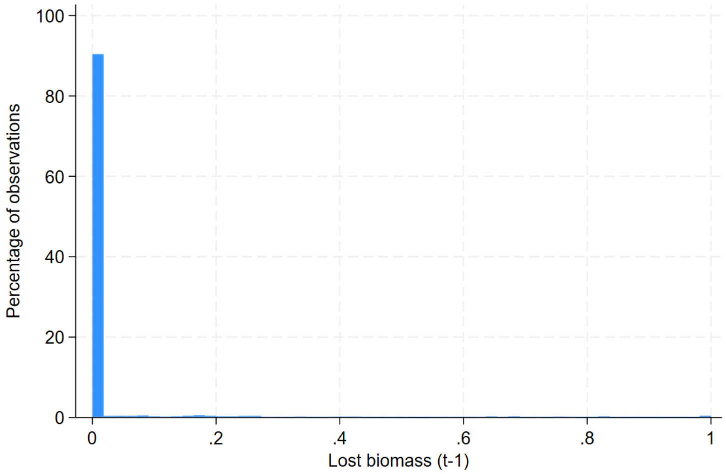

Figure CVII: Histogram of Lost Biomass (Independent Transition)

Appendix D

Table DI: Summary Statistics (Cross-Country)

	Mean	SD	Min	Max	N
Dependent variable					
Years elapsed since the NR (in 100 years)	46.83	24.64	2.44	105.00	171
Independent variables					
Lost biomass (herbivore > 44 kg)	0.50	0.41	0.00	1.00	164
Lost biomass (herbivore <= 44 kg)	0.02	0.08	0.00	0.63	173
Lost biomass (non-herbivore)	0.02	0.11	0.00	1.00	174
Lost biomass (Currie, 1993)	0.40	0.32	0.00	1.00	171
Lost biomass (Damuth, 1987)	0.36	0.29	0.00	1.00	171
Lost biomass (Peters and Raelson, 1984)	0.32	0.27	0.00	1.00	171
Lost biomass (Peters and Wassenberg, 1983)	0.39	0.32	0.00	1.00	171
Lost biomass (Silva et al., 2001)	0.37	0.30	0.00	1.00	171
Instrumental variable					
Lost biomass (IV)	0.80	0.11	0.29	0.99	164
Control variables					
Dist. to the closest agr. origin	2581.06	1312.10	0.00	7157.67	236
Migratory dist. from Addis Ababa	8113.31	6789.63	0.00	26770.69	151
Paleo-temperature (mean)	13.43	10.90	-28.12	24.82	181
Paleo-precipitation (mean)	1054.87	714.36	39.83	3042.57	181
Paleo-temperature (std.)	2.18	1.98	0.00	9.64	181
Paleo-precipitation (std.)	277.08	242.23	0.00	1088.64	181
Paleo-net primary productivity	483.06	363.47	0.00	1476.94	181
Absolute latitude	25.35	17.05	1.00	72.00	200
Caloric suitability (mean)	6456.55	3696.62	0.00	17993.70	223
Terrain ruggedness	130052.46	125672.51	0.00	670995.75	234
Island	0.33	0.47	0.00	1.00	224
Area	573490.07	1746482.05	0.71	16973512.00	234
Dist. to the closest waterway	334.69	467.52	7.95	2385.58	164
Animals	3.74	4.16	0.00	9.00	141
Plants	13.29	13.60	0.00	33.00	141
Extinction rate	0.24	0.22	0.00	0.77	124
Intermonthly temperature vol.	4.50	2.78	0.55	10.08	117
Temperature (seasonality)	9.45	7.06	0.00	28.04	119
Precipitation (seasonality)	1.47	0.69	0.27	3.21	119

Table DII: Summary Statistics (Archaeological Site Panel)

	Mean	SD	Min	Max	N
Dependent variable					
Independent Neolithic Revolution indicator	0.06	0.24	0.00	1.00	8532
Independent variables					
Lost biomass (t-1)	0.02	0.09	0.00	1.00	8412
Lost biomass (t+1)	0.02	0.10	0.00	1.00	8397
Lost biomass (Currie, 1993) (t-1)	0.02	0.08	0.00	1.00	7904
Lost biomass (Damuth, 1987) (t-1)	0.01	0.07	0.00	1.00	7904
Lost biomass (Peters and Raelson, 1984) (t-1)	0.01	0.06	0.00	1.00	7904
Lost biomass (Peters and Wassenberg, 1983) (t-1)	0.02	0.08	0.00	1.00	7904
Lost biomass (Silva et al., 2001) (t-1)	0.02	0.08	0.00	1.00	7904
Instrumental variable					
Lost biomass (IV) (t-1)	0.04	0.00	0.03	0.04	7953
Control variables					
Paleo-temperature (mean) (t-1)	11.42	8.58	-20.27	28.13	8417
Paleo-precipitation (mean) (t-1)	946.44	512.14	50.27	3956.11	8417
Paleo-temperature (std.) (t-1)	0.65	0.71	0.00	4.79	8417
Paleo-precipitation (std.) (t-1)	76.29	79.46	0.00	731.14	8417
Paleo-net primary productivity (t-1)	398.68	262.02	0.00	1872.96	8417
Intermonthly temperature vol. (t-1)	7.05	2.54	0.35	16.92	7937
Temperature (seasonality) (t-1)	14.90	6.32	0.00	34.01	8417
Precipitation (seasonality) (t-1)	140.01	74.36	16.34	334.05	8417

Table DIII: Summary Statistics (Independent Transition Panel)

	Mean	SD	Min	Max	N
Dependent variable					
Independent Neolithic Revolution indicator	0.00	0.04	0.00	1.00	404337
Independent variables					
Lost biomass (t-1)	0.04	0.14	0.00	1.00	343657
Lost biomass (t+1)	0.04	0.15	0.00	1.00	326308
Lost biomass (Currie, 1993) (t-1)	0.03	0.13	0.00	1.00	331626
Lost biomass (Damuth, 1987) (t-1)	0.03	0.12	0.00	1.00	331626
Lost biomass (Peters and Raelson, 1984) (t-1)	0.03	0.11	0.00	1.00	331626
Lost biomass (Peters and Wassenberg, 1983) (t-1)	0.03	0.13	0.00	1.00	331626
Lost biomass (Silva et al., 2001) (t-1)	0.03	0.13	0.00	1.00	331626
Instrumental variable					
Lost biomass (IV) (t-1)	0.04	0.00	0.03	0.04	344234
Control variables					
Paleo-temperature (mean) (t-1)	3.64	17.71	-45.83	30.15	390201
Paleo-precipitation (mean) (t-1)	657.76	689.12	0.00	7285.33	390201
Paleo-temperature (std.) (t-1)	0.52	0.64	0.00	9.43	390201
Paleo-precipitation (std.) (t-1)	43.19	82.27	0.00	2121.54	390201
Paleo-net primary productivity (t-1)	345.39	376.82	0.00	2271.00	390201
Intermonthly temperature vol. (t-1)	9.87	6.37	0.25	30.33	378241
Temperature (seasonality) (t-1)	9.98	7.40	0.00	41.91	390201
Precipitation (seasonality) (t-1)	167.35	76.57	8.07	365.00	389857

Table DIV: Hunting Dependency and Lost Biomass

	Hunting dependency					
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS
Lost biomass	-0.400***	-0.315***	-0.378***	-0.365***	-0.319***	-0.296***
	(0.087)	(0.053)	(0.048)	(0.051)	(0.059)	(0.063)
Paleo-temperature (mean)		-0.364***	-0.156***	-0.170***	-0.111*	-0.161**
		(0.050)	(0.052)	(0.054)	(0.065)	(0.071)
Paleo-precipitation (mean)		-0.033	0.155***	0.080	0.069	0.087
		(0.036)	(0.046)	(0.070)	(0.074)	(0.068)
Paleo-temperature (std.)			0.305***	0.314***	0.405***	0.340***
			(0.086)	(0.088)	(0.105)	(0.103)
Paleo-precipitation (std.)			-0.127**	-0.096*	-0.058	-0.037
			(0.053)	(0.055)	(0.060)	(0.058)
Paleo-net primary productivity				0.074	0.053	0.023
				(0.054)	(0.061)	(0.084)
Dist. to the closest agr. center					0.157***	0.166***
					(0.057)	(0.057)
Migratory distance from Addis Ababa					0.226	0.179
					(0.136)	(0.132)
Absolute latitude						0.004
						(0.097)
Caloric suitability pre-1500 CE						0.002
						(0.049)
Terrain ruggedness						-0.056
						(0.038)
Island						-0.005
						(0.018)
Area						0.097**
						(0.037)
Dist. to the closest waterways						0.034**
						(0.016)
Continent FE	✓	✓	✓	✓	✓	✓
Outcome mean	1.515	1.515	1.515	1.515	1.515	1.515
Outcome std.	1.587	1.587	1.587	1.587	1.587	1.587
Adjusted R^2	0.400	0.479	0.494	0.495	0.506	0.510
Observations	1151	1151	1151	1151	1151	1151

Note: The unit of analysis is an ethnic group as reported by the *Ethnographic Atlas*. Continent fixed effects include Africa, Americas, Asia, Europe, and Oceania. All variables are standardized. Robust standard errors are clustered at the language group level. *** p<0.01, ** p<0.05, * p<0.10.

Table DV: Extinction, Limb Inefficiency, and Digestive Inefficiency

	(1) Logit	(2) Logit	(3) Logit	(4) Logit	(5) Logit
Dummy extinction					
Limb inefficiency	1.091***		0.619**		0.607**
	(0.231)		(0.264)		(0.266)
Digestive inefficiency		1.145***	0.849***		0.837***
		(0.215)	(0.234)		(0.248)
Body mass				0.960**	0.050
				(0.400)	(0.263)
Outcome mean	0.505	0.505	0.505	0.505	0.505
Outcome std.	0.501	0.501	0.501	0.501	0.501
Pseudo-R^2	0.142	0.187	0.213	0.059	0.213
Observations	182	182	182	182	182

Note: The unit of analysis is a mammalian species. All the independent variables are standardized. Robust standard errors are reported. *** p<0.01, ** p<0.05, * p<0.10.

Table DVI: The Neolithic Revolution and Lost Biomass Calculated from Other Studies (Cross-Country)

	Years elapsed since the Neolithic Revolution				
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS
Lost biomass (Currie, 1993)	0.286*** (0.079)				
Lost biomass (Damuth, 1987)		0.259*** (0.086)			
Lost biomass (Peters and Raelson, 1984)			0.231** (0.093)		
Lost biomass (Peters and Wassenberg, 1983)				0.282*** (0.080)	
Lost biomass (Silva et al., 2001)					0.273*** (0.082)
Continent FE	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓
Outcome mean	49.450	49.450	49.450	49.450	49.450
Outcome std.	23.617	23.617	23.617	23.617	23.617
Adjusted R^2	0.854	0.848	0.844	0.853	0.851
Observations	140	140	140	140	140

Note: The unit of analysis is a country. Lost biomass for each row is calculated using different estimated relationships between species' body mass and abundance, as indicated in the parentheses. Continent fixed effects include Africa, the Americas, Asia, Europe, and Oceania. Controls include the means and standard deviations of paleo-temperature and paleo-precipitation, paleo-net primary productivity, the distance to the nearest agricultural origin, migratory distance to Addis Ababa, absolute latitude, caloric suitability, terrain ruggedness, island status, area, and the distance to the nearest waterway. All variables are standardized. Robust standard errors are reported. *** p<0.01, ** p<0.05, * p<0.10.

Table DVII: Recalculated Lost Biomass Including 14 Domesticable Mammals (Cross-Country)

	Years elapsed since the Neolithic Revolution							
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) 2SLS
Lost biomass	0.129*	0.431***	0.412***	0.444***	0.436***	0.276***	0.303***	1.122***
	(0.075)	(0.101)	(0.094)	(0.103)	(0.099)	(0.080)	(0.100)	(0.227)
Paleo-temperature (mean)			0.354***	0.551***	0.565***	0.450***	0.468***	0.294
			(0.073)	(0.089)	(0.085)	(0.079)	(0.121)	(0.182)
Paleo-precipitation (mean)			-0.212***	-0.100	0.032	0.067	0.083	0.318**
			(0.063)	(0.080)	(0.111)	(0.085)	(0.086)	(0.154)
Paleo-temperature (std.)				0.244***	0.228***	0.189***	0.186***	0.203**
				(0.056)	(0.057)	(0.051)	(0.064)	(0.079)
Paleo-precipitation (std.)				-0.180**	-0.188**	-0.108	-0.118*	-0.328***
				(0.075)	(0.072)	(0.067)	(0.070)	(0.093)
Paleo-net primary productivity					-0.179	-0.209**	-0.125	-0.207
					(0.113)	(0.093)	(0.127)	(0.174)
Dist. to the closest agr. origin						-0.267***	-0.235***	-0.018
						(0.052)	(0.052)	(0.090)
Migratory dist. from Addis Ababa						-0.392**	-0.393**	-0.466**
						(0.154)	(0.156)	(0.222)
Continent FE		✓	✓	✓	✓	✓	✓	✓
Additional geographic controls							✓	✓
Outcome mean	49.450	49.450	49.450	49.450	49.450	49.450	49.450	49.450
Outcome std.	23.617	23.617	23.617	23.617	23.617	23.617	23.617	23.617
First stage F								30.596
Adjusted R^2	0.011	0.675	0.734	0.764	0.766	0.846	0.850	
Observations	140	140	140	140	140	140	140	140

Note: The unit of analysis is a country. Lost biomass is calculated including the 14 domesticable mammal species. Continent fixed effects include Africa, the Americas, Asia, Europe, and Oceania. Additional geographic controls include absolute latitude, mean caloric suitability, terrain ruggedness, island dummy, area, and the distance to the closest waterway. All variables are standardized. Robust standard errors are reported. *** p<0.01, ** p<0.05, * p<0.10.

Table DVIII: Adding Domesticable Animals and Plants, and Extinction Rate (Cross-Country)

	Years elapsed since the Neolithic Revolution				
	(1) OLS	(2) 2SLS	(3) OLS	(4) OLS	(5) 2SLS
Lost biomass	0.145	1.014***		0.255***	1.028***
	(0.108)	(0.320)		(0.096)	(0.311)
Animals	0.165	-0.128			
	(0.160)	(0.243)			
Plants	0.155	0.129			
	(0.178)	(0.164)			
Extinction rate			1.348***	0.170	-0.690
			(0.314)	(0.191)	(0.426)
Extinction rate (sqr.)			-1.191***	0.096	0.408*
			(0.323)	(0.143)	(0.245)
Paleo-temperature (mean)	0.314**	0.290*		0.292**	0.138
	(0.137)	(0.172)		(0.138)	(0.161)
Paleo-precipitation (mean)	-0.029	0.291		0.129*	0.274**
	(0.091)	(0.191)		(0.075)	(0.108)
Paleo-temperature (std.)	0.152**	0.216***		0.182***	0.165**
	(0.067)	(0.074)		(0.062)	(0.065)
Paleo-precipitation (std.)	-0.038	-0.291**		-0.219***	-0.293***
	(0.080)	(0.115)		(0.067)	(0.078)
Paleo-net primary productivity	-0.088	-0.244		-0.274**	-0.344**
	(0.133)	(0.193)		(0.106)	(0.136)
Dist. to the closest agr. origin	-0.280***	-0.024		-0.206***	-0.078
	(0.055)	(0.111)		(0.054)	(0.081)
Migratory dist. from Addis Ababa	-0.188	-0.381*		-0.331**	-0.437**
	(0.197)	(0.217)		(0.165)	(0.191)
Absolute latitude	-0.075	-0.457*		-0.205*	-0.347**
	(0.145)	(0.243)		(0.119)	(0.145)
Caloric suitability (mean)	0.049	-0.056		-0.057	-0.037
	(0.082)	(0.096)		(0.065)	(0.071)
Terrain ruggedness	-0.008	-0.070		-0.024	-0.056
	(0.045)	(0.060)		(0.039)	(0.048)
Island	-0.156*	-0.231		-0.064	0.108
	(0.084)	(0.196)		(0.074)	(0.203)
Area	0.073*	0.108		0.042	0.103**
	(0.039)	(0.066)		(0.031)	(0.047)
Dist. to the closest waterway	-0.075	-0.212*		-0.147***	-0.311***
	(0.069)	(0.116)		(0.044)	(0.083)
Continent FE	✓	✓		✓	✓
Outcome mean	45.732	45.732	47.737	47.737	47.737
Outcome std.	23.276	23.276	23.373	23.373	23.373
First stage F		17.068			13.733
Adjusted R^2	0.863		0.146	0.897	
Observations	114	114	114	114	114

Note: The unit of analysis is a country. Animals and Plants refer to the number of domesticable species, as reported by Olsson and Hibbs (2005). Extinction rate represents the ratio of extinct large mammals, as reported by Sandom et al. (2014). Continent fixed effects include Africa, the Americas, Asia, Europe, and Oceania. All variables are standardized. Robust standard errors are reported. *** p<0.01, ** p<0.05, * p<0.10.

Table DIX: Adding Intermonthly Temperature Volatility and Climatic Seasonality (Cross-Country)

	Years elapsed since the Neolithic Revolution				
	(1) OLS	(2) 2SLS	(3) OLS	(4) OLS	(5) 2SLS
Lost biomass	0.220	1.253***		0.193*	0.741***
	(0.143)	(0.348)		(0.104)	(0.246)
Intermonthly temperature vol.	0.645	-0.281			
	(0.506)	(0.826)			
Intermonthly temperature vol. sqr.	-0.659*	-0.303			
	(0.390)	(0.542)			
Temperature (seasonality)			0.440***	0.404***	0.258**
			(0.053)	(0.085)	(0.110)
Precipitation (seasonality)			0.059	0.006	0.042
			(0.053)	(0.051)	(0.059)
Paleo-temperature (mean)	0.278	0.331		0.002	0.013
	(0.207)	(0.321)		(0.153)	(0.188)
Paleo-precipitation (mean)	-0.072	-0.042		0.218**	0.345***
	(0.112)	(0.174)		(0.094)	(0.125)
Paleo-temperature (std.)	0.164**	0.276***		0.198***	0.199**
	(0.074)	(0.094)		(0.066)	(0.083)
Paleo-precipitation (std.)	-0.149*	-0.322**		-0.122	-0.255***
	(0.086)	(0.125)		(0.080)	(0.095)
Paleo-net primary productivity	0.004	0.073		-0.148	-0.239
	(0.152)	(0.183)		(0.151)	(0.189)
Dist. to the closest agr. origin	-0.295***	-0.152*		-0.174***	-0.058
	(0.059)	(0.091)		(0.056)	(0.092)
Migratory dist. from Addis Ababa	-0.311*	-0.014		-0.331**	-0.467***
	(0.168)	(0.248)		(0.149)	(0.177)
Absolute latitude	-0.210	-0.076		-0.345**	-0.566**
	(0.256)	(0.463)		(0.160)	(0.233)
Caloric suitability (mean)	-0.073	-0.067		-0.036	-0.040
	(0.094)	(0.107)		(0.072)	(0.077)
Terrain ruggedness	-0.000	-0.016		-0.060	-0.083
	(0.042)	(0.064)		(0.062)	(0.068)
Island	-0.171*	-0.316		0.011	-0.015
	(0.097)	(0.218)		(0.107)	(0.197)
Area	0.150***	0.140		0.001	0.065
	(0.047)	(0.094)		(0.034)	(0.051)
Dist. to the closest waterway	-0.234**	-0.220*		-0.113*	-0.211***
	(0.100)	(0.117)		(0.057)	(0.070)
Continent FE	✓	✓	✓	✓	✓
Outcome mean	46.864	46.864	48.733	48.733	48.733
Outcome std.	22.248	22.248	23.020	23.020	23.020
First stage F		15.313			13.782
Adjusted R^2	0.859		0.769	0.869	
Observations	103	103	105	105	105

Note: The unit of analysis is a country. Intermonthly temperature volatility and its square term are taken from Ashraf and Michalopoulos (2015). The seasonality of temperature and precipitation are calculated from Matranga (2024). Continent fixed effects include Africa, the Americas, Asia, Europe, and Oceania. All variables are standardized. Robust standard errors are reported. *** p<0.01, ** p<0.05, * p<0.10.

Table DX: Conley Standard Error Calculation (Cross-Country)

	Years elapsed since the Neolithic Revolution					
	(1) OLS (2000 km)	(2) 2SLS (2000 km)	(3) OLS (2500 km)	(4) 2SLS (2500 km)	(5) OLS (3000 km)	(6) 2SLS (3000 km)
Lost biomass	0.286***	0.917***	0.286***	0.917***	0.286***	0.917***
	(0.096)	(0.217)	(0.098)	(0.210)	(0.099)	(0.204)
Paleo-temperature (mean)	0.535***	0.352*	0.535***	0.352*	0.535***	0.352*
	(0.146)	(0.212)	(0.148)	(0.210)	(0.150)	(0.208)
Paleo-precipitation (mean)	0.196*	0.389**	0.196*	0.389**	0.196*	0.389**
	(0.107)	(0.151)	(0.107)	(0.152)	(0.107)	(0.152)
Paleo-temperature (std.)	0.224***	0.204**	0.224***	0.204**	0.224***	0.204**
	(0.071)	(0.092)	(0.074)	(0.090)	(0.076)	(0.089)
Paleo-precipitation (std.)	-0.174**	-0.309***	-0.174**	-0.309***	-0.174*	-0.309***
	(0.088)	(0.102)	(0.088)	(0.102)	(0.091)	(0.101)
Paleo-net primary productivity	-0.251	-0.384*	-0.251	-0.384*	-0.251	-0.384*
	(0.158)	(0.198)	(0.160)	(0.197)	(0.162)	(0.196)
Dist. to the closest agr. origin	-0.223***	-0.054	-0.223***	-0.054	-0.223***	-0.054
	(0.061)	(0.097)	(0.062)	(0.094)	(0.061)	(0.091)
Migratory dist. from Addis Ababa	-0.479***	-0.588***	-0.479**	-0.588***	-0.479**	-0.588***
	(0.180)	(0.216)	(0.186)	(0.220)	(0.190)	(0.223)
Absolute latitude	0.104	-0.397	0.104	-0.397	0.104	-0.397
	(0.174)	(0.285)	(0.179)	(0.280)	(0.182)	(0.277)
Caloric suitability (mean)	-0.022	-0.039	-0.022	-0.039	-0.022	-0.039
	(0.085)	(0.107)	(0.083)	(0.108)	(0.082)	(0.108)
Terrain ruggedness	0.050	-0.032	0.050	-0.032	0.050	-0.032
	(0.068)	(0.085)	(0.069)	(0.083)	(0.071)	(0.082)
Island	-0.071	-0.085	-0.071	-0.085	-0.071	-0.085
	(0.124)	(0.241)	(0.126)	(0.244)	(0.128)	(0.247)
Area	0.014	0.090	0.014	0.090	0.014	0.090
	(0.037)	(0.059)	(0.038)	(0.060)	(0.038)	(0.060)
Dist. to the closest waterway	-0.059	-0.193***	-0.059	-0.193***	-0.059	-0.193***
	(0.061)	(0.073)	(0.062)	(0.073)	(0.062)	(0.073)
Continent FE	✓	✓	✓	✓	✓	✓
Outcome mean	48.732	48.732	48.732	48.732	48.732	48.732
Outcome std.	23.542	23.542	23.542	23.542	23.542	23.542
First stage F		14.615		14.501		14.300
Observations	99	99	99	99	99	99

Note: The unit of analysis is a country. Continent fixed effects include Africa, the Americas, Asia, Europe, and Oceania. All variables are standardized. Robust standard errors are in parentheses calculated using the spatial correlation proposed by Conley (1999) with a threshold of 2000 (columns 1 and 2), 2500 (columns 3 and 4) and 3000 (columns 5 and 6) kilometers. *** p<0.01, ** p<0.05, * p<0.10.

Table DXI: The Neolithic Revolution and Lost Biomass (Cross-Archaeological Site)

	Years elapsed since the Neolithic Revolution							
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) 2SLS
Lost biomass	0.491***	0.428***	0.119***	0.155***	0.156***	0.140***	0.061**	0.265***
	(0.052)	(0.100)	(0.035)	(0.032)	(0.032)	(0.033)	(0.030)	(0.083)
Paleo-temperature (mean)				0.064*	0.073**	0.044	0.145**	0.188***
				(0.035)	(0.034)	(0.035)	(0.067)	(0.067)
Paleo-precipitation (mean)				-0.095***	-0.079**	-0.139***	-0.095**	-0.092**
				(0.028)	(0.033)	(0.034)	(0.038)	(0.039)
Paleo-temperature (std.)					0.051**	0.049**	0.014	0.013
					(0.024)	(0.024)	(0.027)	(0.027)
Paleo-precipitation (std.)					-0.043*	-0.032	0.004	-0.007
					(0.023)	(0.022)	(0.021)	(0.022)
Paleo-net primary productivity						0.124***	0.005	0.022
						(0.030)	(0.041)	(0.040)
Dist. to the closest agr. origin							-0.320***	-0.288***
							(0.034)	(0.034)
Migratory dist. from Addis Ababa							0.004	0.023
							(0.030)	(0.037)
Absolute latitude							0.011	-0.032
							(0.081)	(0.083)
Caloric suitability (mean)							-0.036	-0.085**
							(0.031)	(0.036)
Terrain ruggedness							0.043	0.033
							(0.033)	(0.033)
Island							0.006	0.006
							(0.018)	(0.016)
Area							0.053**	0.063**
							(0.023)	(0.024)
Dist. to the closest waterway							0.002	0.010
							(0.021)	(0.021)
Continent FE		✓	✓	✓	✓	✓	✓	✓
Data source FE			✓	✓	✓	✓	✓	✓
Outcome mean	57.862	57.862	57.862	57.862	57.862	57.862	57.862	57.862
Outcome std.	24.095	24.095	24.095	24.095	24.095	24.095	24.095	24.095
First stage F								33.888
Adjusted R^2	0.241	0.263	0.859	0.865	0.867	0.873	0.907	
Observations	470	470	470	470	470	470	470	470

Note: The unit of analysis is a 1° × 1° grid cell. The dependent variable is the years elapsed since the Neolithic Revolution in 100 years. Continent fixed effects include Africa, Asia, and Europe. Data source fixed effects are indicators if the data sources from Pinhasi and Ammerman (2005) or Cobo et al. (2019). All variables are standardized. Standard errors are clustered at the neighboring 2-degree by 2-degree grid cell level. *** p<0.01, ** p<0.05, * p<0.10.

Table DXII: The Neolithic Revolution and Lost Biomass Calculated from Other Studies (Archaeological Site Panel)

	The NR indicator				
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS
Lost biomass (Currie, 1993)	0.113*** (0.021)				
Lost biomass (Damuth, 1987)		0.118*** (0.022)			
Lost biomass (Peters and Raelson, 1984)			0.122*** (0.022)		
Lost biomass (Peters and Wassenberg, 1983)				0.114*** (0.021)	
Lost biomass (Silva et al., 2001)					0.116*** (0.021)
Cell FE	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓
Paleo-Climate Controls	✓	✓	✓	✓	✓
Outcome mean	0.060	0.060	0.060	0.060	0.060
Outcome std.	0.238	0.238	0.238	0.238	0.238
Adjusted R-Sqr.	0.319	0.319	0.319	0.319	0.319
Observations	7850	7850	7850	7850	7850

Note: The unit of analysis is a 1° × 1° grid cell. The dependent variable is a dummy that equals 1 if a grid cell undergoes an agricultural transition and 0 otherwise. The panel spans from 21,000 BP until the transition occurs, using 1,000-year time windows. Lost biomass for each row is calculated using different estimated relationships between species' body mass and abundance, as indicated in the parentheses. Paleo-climate controls include the means and standard deviations of paleo-temperature and paleo-precipitation, and paleo-net primary productivity. All variables are standardized. Robust standard errors, clustered at the grid cell level, are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

Table DXIII: Recalculated Lost Biomass Including 14 Domesticable Mammals (Archaeological Site Panel)

	The NR indicator							
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS
Lost biomass (t-1)	0.104*** (0.018)	0.103*** (0.018)	0.103*** (0.018)	0.100*** (0.018)				
Lost biomass (t+1)					0.012 (0.018)	0.004 (0.018)	0.002 (0.018)	0.002 (0.018)
Paleo-temperature (mean) (t-1)		0.284*** (0.076)	0.380*** (0.081)	0.609*** (0.085)		0.312*** (0.078)	0.417*** (0.082)	0.645*** (0.086)
Paleo-precipitation (mean) (t-1)		-0.580*** (0.060)	-0.613*** (0.063)	-0.367*** (0.070)		-0.567*** (0.061)	-0.601*** (0.063)	-0.354*** (0.071)
Paleo-temperature (std.) (t-1)			0.161** (0.074)	0.063 (0.075)			0.178** (0.071)	0.079 (0.073)
Paleo-precipitation (std.) (t-1)			0.124** (0.048)	0.074 (0.048)			0.124** (0.049)	0.074 (0.049)
Paleo-net primary productivity (t-1)				-0.497*** (0.069)				-0.499*** (0.069)
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓
Outcome mean	0.060	0.060	0.060	0.060	0.059	0.059	0.059	0.059
Outcome std.	0.237	0.237	0.237	0.237	0.235	0.235	0.235	0.235
Adjusted R-Sqr.	0.298	0.313	0.314	0.320	0.289	0.304	0.305	0.312
Observations	8385	8385	8385	8385	8370	8370	8370	8370

Note: The unit of analysis is a 1° × 1° grid cell. The dependent variable is a dummy that equals 1 if a grid cell undergoes an agricultural transition and 0 otherwise. The panel spans from 21,000 BP until the transition occurs, using 1,000-year time windows. Lost biomass is calculated including the 14 domesticable mammal species. All variables are standardized. Robust standard errors, clustered at the grid cell level, are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

Table DXIV: Adding Intermonthly Temperature Volatility and Climatic Seasonality (Archaeological Site Panel)

	The NR indicator							
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS
Lost biomass (t-1)	0.114***	0.113***	0.113***	0.110***	0.116***	0.121***	0.122***	0.120***
	(0.020)	(0.019)	(0.020)	(0.020)	(0.025)	(0.025)	(0.025)	(0.025)
Intermonthly temperature vol. (t-1)	0.004	-0.106	-0.093	-0.284				
	(0.440)	(0.419)	(0.417)	(0.392)				
Intermonthly temperature vol. sqr. (t-1)	0.984***	0.882**	0.892**	1.042***				
	(0.376)	(0.377)	(0.376)	(0.344)				
Temperature (seasonality) (t-1)					1.622***	1.519***	1.502***	1.445***
					(0.118)	(0.133)	(0.133)	(0.131)
Precipitation (seasonality) (t-1)					-0.217*	-0.149	-0.152	-0.193*
					(0.115)	(0.114)	(0.114)	(0.117)
Paleo-temperature (mean) (t-1)		0.024	0.134	0.352***		-0.110	-0.017	0.305**
		(0.101)	(0.106)	(0.103)		(0.103)	(0.122)	(0.127)
Paleo-precipitation (mean) (t-1)		-0.594***	-0.629***	-0.378***		-0.301***	-0.328***	-0.052
		(0.061)	(0.064)	(0.071)		(0.070)	(0.073)	(0.079)
Paleo-temperature (std.) (t-1)			0.199**	0.094			0.118	0.015
			(0.078)	(0.078)			(0.109)	(0.106)
Paleo-precipitation (std.) (t-1)			0.131***	0.082*			0.089	0.050
			(0.049)	(0.049)			(0.064)	(0.063)
Paleo-net primary productivity (t-1)				-0.502***				-0.518***
				(0.071)				(0.083)
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓
Outcome mean	0.063	0.063	0.063	0.063	0.069	0.069	0.069	0.069
Outcome std.	0.244	0.244	0.244	0.244	0.253	0.253	0.253	0.253
Adjusted R-Sqr.	0.305	0.315	0.316	0.323	0.332	0.334	0.334	0.339
Observations	7850	7850	7850	7850	5725	5725	5725	5725

Note: The unit of analysis is a $1^\circ \times 1^\circ$ grid cell. The dependent variable is a dummy that equals 1 if a grid cell undergoes an agricultural transition and 0 otherwise. The panel spans from 21,000 BP until the transition occurs, using 1,000-year time windows. All variables are standardized. Robust standard errors, clustered at the grid cell level, are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

Table DXV: Spatial Standard Error Correction (Archaeological Site Panel)

	1.5° × 1.5°	2° × 2°	2.5° × 2.5°	150 km	200 km	250 km
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS
Lost biomass (t-1)	0.104***	0.104***	0.104***	0.104***	0.104***	0.104***
	(0.019)	(0.022)	(0.024)	(0.021)	(0.022)	(0.024)
Paleo-temperature (mean) (t-1)	0.649***	0.649***	0.649***	0.649***	0.649***	0.649***
	(0.112)	(0.120)	(0.136)	(0.114)	(0.127)	(0.139)
Paleo-precipitation (mean) (t-1)	-0.372***	-0.372***	-0.372***	-0.372***	-0.372***	-0.372***
	(0.081)	(0.082)	(0.093)	(0.080)	(0.085)	(0.089)
Paleo-temperature (std.) (t-1)	0.071	0.071	0.071	0.071	0.071	0.071
	(0.083)	(0.082)	(0.078)	(0.081)	(0.082)	(0.083)
Paleo-precipitation (std.) (t-1)	0.077	0.077	0.077	0.077	0.077	0.077
	(0.050)	(0.051)	(0.056)	(0.049)	(0.051)	(0.053)
Paleo-net primary productivity (t-1)	-0.499***	-0.499***	-0.499***	-0.499***	-0.499***	-0.499***
	(0.084)	(0.088)	(0.092)	(0.080)	(0.086)	(0.093)
Cell FE	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓
Outcome mean	0.063	0.063	0.063	0.063	0.063	0.063
Outcome std.	0.244	0.244	0.244	0.244	0.244	0.244
Adjusted R-Sqr.	0.318	0.318	0.318			
Observations	7850	7850	7850	7850	7850	7850

Note: The unit of analysis is a 1° × 1° grid cell, and all variables are standardized. The dependent variable is a dummy that equals 1 if a grid cell undergoes an independent agricultural transition and 0 otherwise. The panel spans from 21,000 BP until the transition occurs, using 1,000-year time windows. Columns 1-3 cluster standard errors at the neighboring x degrees by x degrees ($x = 1.5, 2, 2.5$) grid cell level. In columns 4, 5, and 6, robust standard errors are calculated using the spatial correlation method proposed by Conley (1999) with distance thresholds of 150 km, 200 km, and 250 km, respectively. *** p<0.01, ** p<0.05, * p<0.10.

Table DXVI: The Neolithic Revolution and Lost Biomass Calculated from Other Studies (Independent Transition)

	The independent NR indicator				
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS
Lost biomass (Currie, 1993)	0.022*** (0.006)				
Lost biomass (Damuth, 1987)		0.021*** (0.006)			
Lost biomass (Peters and Raelson, 1984)			0.020*** (0.006)		
Lost biomass (Peters and Wassenberg, 1983)				0.022*** (0.006)	
Lost biomass (Silva et al., 2001)					0.022*** (0.006)
Cell FE	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓
Paleo-Climate Controls	✓	✓	✓	✓	✓
Outcome mean	0.002	0.002	0.002	0.002	0.002
Outcome std.	0.046	0.046	0.046	0.046	0.046
Adjusted R-Sqr.	0.030	0.030	0.030	0.030	0.030
Observations	322279	322279	322279	322279	322279

Note: The unit of analysis is a $1^\circ \times 1^\circ$ grid cell. The dependent variable is a dummy that equals 1 if a grid cell undergoes an independent agricultural transition and 0 otherwise. The panel spans from 21,000 BP until the transition occurs, using 1,000-year time windows. Lost biomass for each row is calculated using different estimated relationships between species' body mass and abundance, as indicated in the parentheses. Paleo-climate controls include the means and standard deviations of paleo-temperature and paleo-precipitation, and paleo-net primary productivity. All variables are standardized. Robust standard errors, clustered at the grid cell level, are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

Table DXVII: Recalculated Lost Biomass Including 14 Domesticable Mammals (Independent Transition)

	The independent NR indicator							
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS
Lost biomass (t-1)	0.014***	0.015***	0.015***	0.015***				
	(0.004)	(0.004)	(0.004)	(0.004)				
Lost biomass (t+1)					-0.015***	-0.016***	-0.016***	-0.016***
					(0.001)	(0.001)	(0.001)	(0.001)
Paleo-temperature (mean) (t-1)		-0.283***	-0.273***	-0.275***		-0.293***	-0.282***	-0.285***
		(0.015)	(0.015)	(0.015)		(0.015)	(0.015)	(0.016)
Paleo-precipitation (mean) (t-1)		0.060***	0.052***	0.028		0.055***	0.046**	0.021
		(0.019)	(0.019)	(0.018)		(0.020)	(0.020)	(0.019)
Paleo-temperature (std.) (t-1)			0.024***	0.027***			0.028***	0.031***
			(0.004)	(0.004)			(0.004)	(0.004)
Paleo-precipitation (std.) (t-1)			0.030***	0.037***			0.031***	0.039***
			(0.009)	(0.010)			(0.010)	(0.011)
Paleo-net primary productivity (t-1)				0.044***				0.047***
				(0.015)				(0.016)
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓
Outcome mean	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Outcome std.	0.044	0.044	0.044	0.044	0.045	0.045	0.045	0.045
Adjusted R-Sqr.	0.028	0.029	0.029	0.029	0.025	0.026	0.026	0.026
Observations	360797	360797	360797	360797	344244	344244	344244	344244

Note: The unit of analysis is a 1° × 1° grid cell. The dependent variable is a dummy that equals 1 if a grid cell undergoes an independent agricultural transition and 0 otherwise. The panel spans from 21,000 BP until the transition occurs, using 1,000-year time windows. Lost biomass is calculated including the 14 domesticable mammal species. All variables are standardized. Robust standard errors, clustered at the grid cell level, are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

Table DXVIII: Adding Intermonthly Temperature Volatility and Climatic Seasonality (Independent Transition)

	The NR indicator							
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS
Lost biomass (t-1)	0.014***	0.016***	0.015***	0.015***	0.014***	0.015***	0.015***	0.015***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.005)
Intermonthly temperature vol. (t-1)	1.119***	0.922***	0.987***	0.960***				
	(0.095)	(0.090)	(0.093)	(0.097)				
Intermonthly temperature vol. sqr. (t-1)	-1.091***	-0.735***	-0.772***	-0.753***				
	(0.073)	(0.067)	(0.068)	(0.071)				
Temperature (seasonality) (t-1)					-0.086***	-0.011	-0.009	-0.016
					(0.014)	(0.014)	(0.014)	(0.014)
Precipitation (seasonality) (t-1)					0.052***	0.010	0.009	0.013
					(0.008)	(0.008)	(0.008)	(0.008)
Paleo-temperature (mean) (t-1)		-0.247***	-0.237***	-0.240***		-0.301***	-0.290***	-0.296***
		(0.022)	(0.022)	(0.022)		(0.021)	(0.021)	(0.021)
Paleo-precipitation (mean) (t-1)		0.059***	0.049**	0.033		0.057**	0.047*	0.008
		(0.021)	(0.021)	(0.020)		(0.026)	(0.026)	(0.025)
Paleo-temperature (std.) (t-1)			0.034***	0.036***			0.028***	0.034***
			(0.004)	(0.004)			(0.005)	(0.005)
Paleo-precipitation (std.) (t-1)			0.040***	0.044***			0.032**	0.045***
			(0.010)	(0.011)			(0.013)	(0.014)
Paleo-net primary productivity (t-1)				0.029*				0.076***
				(0.017)				(0.021)
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓
Outcome mean	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Outcome std.	0.046	0.046	0.046	0.046	0.049	0.049	0.049	0.049
Adjusted R-Sqr.	0.030	0.030	0.030	0.030	0.034	0.034	0.034	0.034
Observations	322448	322448	322448	322448	269180	269180	269180	269180

Note: The unit of analysis is a 1° × 1° grid cell. The dependent variable is a dummy that equals 1 if a grid cell undergoes an independent agricultural transition and 0 otherwise. The panel spans from 21,000 BP until the transition occurs, using 1,000-year time windows. All variables are standardized. Robust standard errors, clustered at the grid cell level, are reported in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.10$.

Table DXIX: Spatial Standard Error Correction (Independent Transition)

	1.5° × 1.5°	2° × 2°	2.5° × 2.5°	150 km	200 km	250 km
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS
Lost biomass (t-1)	0.016***	0.016**	0.016*	0.016***	0.016**	0.016*
	(0.006)	(0.006)	(0.008)	(0.006)	(0.007)	(0.008)
Paleo-temperature (mean) (t-1)	-0.291***	-0.291***	-0.291***	-0.291***	-0.291***	-0.291***
	(0.027)	(0.026)	(0.038)	(0.026)	(0.032)	(0.038)
Paleo-precipitation (mean) (t-1)	0.023	0.023	0.023	0.023	0.023	0.023
	(0.029)	(0.028)	(0.039)	(0.029)	(0.034)	(0.039)
Paleo-temperature (std.) (t-1)	0.032***	0.032***	0.032***	0.032***	0.032***	0.032***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.006)
Paleo-precipitation (std.) (t-1)	0.038***	0.038***	0.038***	0.038***	0.038***	0.038***
	(0.013)	(0.013)	(0.014)	(0.012)	(0.013)	(0.014)
Paleo-net primary productivity (t-1)	0.045*	0.045*	0.045	0.045*	0.045	0.045
	(0.024)	(0.026)	(0.032)	(0.024)	(0.028)	(0.033)
Cell FE	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓
Outcome mean	0.002	0.002	0.002	0.002	0.002	0.002
Outcome std.	0.046	0.046	0.046	0.046	0.046	0.046
Adjusted R-Sqr.	0.030	0.030	0.030	.	.	.
Observations	322279	322279	322279	322279	322279	322279

Note: The unit of analysis is a 1° × 1° grid cell, and all variables are standardized. The dependent variable is a dummy that equals 1 if a grid cell undergoes an independent agricultural transition and 0 otherwise. The panel spans from 21,000 BP until the transition occurs, using 1,000-year time windows. Columns 1-3 cluster standard errors at the neighboring x degrees by x degrees ($x = 1.5, 2, 2.5$) grid cell level. In columns 4, 5, and 6, robust standard errors are calculated using the spatial correlation method proposed by Conley (1999) with distance thresholds of 150 km, 200 km, and 250 km, respectively. *** p<0.01, ** p<0.05, * p<0.10.

Appendix E

Outcome Variables

- **Time elapsed since the Neolithic Revolution**: For a country, this refers to the number of years that have passed as of the year 2000 since a substantial population within the country's modern borders began practicing sedentary agriculture as the primary mode of subsistence. The data is sourced from Borcan et al. (2018). For an archaeological site, it refers to the earliest date (in thousands of years before present) of Neolithic settlement, estimated using radiocarbon dating methods. This data is taken from Pinhasi et al. (2005) and Cobo et al. (2019). For the analysis of independent transitions, it refers to the years elapsed since the first domestication. Well-accepted agricultural centers and the associated transition dates are taken from Larson et al. (2014), who also provide specific territories for these seven regions.

- **Hunting dependency**: This is a categorical variable indicating the percentage range of dependence on hunting as a subsistence mode. The data is sourced from the *Ethnographic Atlas*.

- **Extinction dummy**: This is an indicator variable that takes 1 if a species went extinct and 0 otherwise. The data is sourced from the *PHYLACINE*.

Independent Variables

Measures of lost biomass are constructed using data from PHYLACINE (Faurby et al., 2018) and Andermann et al. (2020). Biomass for a species is defined as the product of its average body mass and the number of individuals. The total biomass for an area is the sum of the biomass of all mammal species living there. Species abundance is predicted using the allometric relationship between body mass and population density, with estimates from Silva and Downing (1995) used for the main variable. Lost biomass in an area is then defined as the biomass of extinct species in the area, normalized by the total biomass (extant and extinct) in that area. More detailed description is found in the data and variable construction section in the paper.

- **Lost biomass due to megaherbivore extinction**: This variable is constructed based on the above definition. A megaherbivore is a terrestrial herbivore weighing more than 44 kg.
- **Lost biomass due to small herbivore extinction**: This variable follows the same definition but applies to herbivores weighing less than 44 kg.
- **Lost biomass due to non-herbivore extinction**: This variable includes terrestrial carnivores and omnivores, which form the complement set of megaherbivores and small herbivores.

Instrumental Variables

- **Lost biomass based on predicted extinction probability**: The instrumental variable is constructed using the following procedure. First, the actual extinction status is regressed on limb inefficiency, digestive inefficiency, and body mass using logistic regression for 182 megaherbivore species. Second, extinction risk is calculated from the estimated coefficients for limb and digestive inefficiency, serving as the predicted value of the actual extinction status. Third, the actual extinction status in the original variable is replaced with the predicted extinction risk. Detailed information about the data and variable construction can be found in the relevant section of the paper.
- **Limb inefficiency**: This is a dummy variable that takes 1 if a species is plantigrade and 0 if the species is cursoil (digitigrade or unguligrade). The data is sourced from the *Herbitraits*.
- **Digestive inefficiency**: This variable takes the value 1, 2, and 3 if a species is foregut

ruminant, foregut non-ruminant, or hidgut fermentor, respectively. The data is sourced from the *Herbitraits*.

Control Variables

- **Distance to the Neolithic transition frontier**: This is the geodesic distance from the nearest agricultural origin among the well-established independent agricultural centers reported by Larson et al. (2014). The distance is measured from the nearest borders specified in the study.

- **Migratory distance from Addis Ababa**: This is the distance from Addis Ababa, Ethiopia, passing through five waypoints (Cairo, Istanbul, Phnom Penh, Anadyr, and Prince Rupert). For countries, the distance is taken from Ashraf and Galor (2013). For other units of analysis, it is calculated by the author using ArcGIS Pro 3.1.3.

- **Absolute latitude**: For countries, this is the absolute value of the latitude of the country's capital. For an ethnic group, it is the value of the latitude, as reported by the *Ethnographic Atlas*.

- **Caloric suitability**: This refers to the caloric value of the optimal crop type available before 1500 CE. The data is sourced from Galor and Özak (2016).

- **Island dummy**: For a country, it is an indicator for whether or not a country shares a land border with any other country, as reported by the CIA's World Factbook online. For an archaeoligical site, it is a dummy variable indicating if the land type of an site's geodesic centroid is a "small island" or a "very small island" as reported in the World Countries geographical dataset provided by ESRI.

- **Distance to the nearest waterway**: For countries, this is the shortest distance to a coast, major river, or lake, as reported by G-ECON. For ethnic group-level analysis, it is the distance from the centroid of an area to the nearest coast or river, based on the 1:10m Natural Earth Coastline and 1:10m Natural Earth River + Lake Centerlines datasets.

- **Total land area**: This is the total land area of an associated territory in square kilometers.

- **Paleo-temperature (mean and standard deviation)**: The average and standard deviation of temperature within a given area are calculated using data from Beyer et al. (2020). For cross-sectional analysis, it represents the average across cells in the area up to 10,500 YBP. For panel analyses, it reflects the average and standard deviation across cells in the area for each corresponding period.

- **Paleo-precipitation (mean and standard deviation)**: The average and standard deviation of precipitation within a given area are calculated using data from Beyer et al. (2020). For cross-sectional analysis, it represents the average across cells in the area up to 10,500 YBP. For panel analyses, it reflects the average and standard deviation across cells in the area for each corresponding period.

- **Paleo-net primary productivity**: Net primary productivity for a given area is calculated using data from Beyer et al. (2020). For cross-sectional analyses, it represents the average across cells in the area up to 10,500 YBP. For panel analyses, it is the average across cells in the area for each corresponding period.

- **Intermonthly temperature volatility**: This refers to the standard deviation of monthly temperature across months. For the cross-country analysis, the data is sourced from Ashraf and Michalopoulos (2015). The construction for panel analyses is as follows: For the starting year, temperature volatility is calculated as the standard deviation of monthly temperatures within that year. For subsequent periods, it is computed using all previous monthly temperature data up to the corresponding period. Temperature volatility is first calculated at the grid-cell level and then aggregated to the relevant unit by averaging across the grid cells within the unit's borders. The temperature data is sourced from Beyer et al. (2020).

- **Climatic seasonality**: For the cross-country analysis, temperature and precipitation seasonality are averaged across points within each country over the available time periods, as reported by Matranga (2024). For grid-cell panel analyses, it is the average of the points within each cell for the corresponding period, using the same data source.

- **Number of domesticable animals and plants**: These refer to the number of domesticable species of animals and plants. The data is sourced from Olsson and Hibbs (2005).

- **Extinction rate**: The percentage of known extinct mammalian species larger than 10 kg relative to the total number of extinct and extant mammalian species larger than 10 kg, from the Late Pleistocene to the early Holocene (132,000 to 1,000 years before present). The data is sourced from Sandom et al. (2014).

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