

Overkill, Extinction, and the Neolithic Revolution*

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Abstract

This research explores the biogeographical and economic origins of the emergence and spread of agriculture. The theory suggests that mammal species with certain biological traits were more vulnerable to hunting, resulting in human-driven extinctions and the loss of hunting resources. This scarcity created economic incentives that encouraged the agricultural transition. To test this hypothesis, I construct a novel measure of resource loss from extinction. Using granular grid-cell panel data and controlling for ancient climate as well as cell and time fixed effects, I show that megaherbivore extinction triggered both the independent rise and the diffusion of farming. The results are robust to an instrumental variable strategy that employs extinction-prone traits as exogenous variation. The effect is especially strong in regions with greater land suitability for agriculture, supporting the economic-incentive mechanism and offering new insights into literature that downplays the role of agricultural productivity in the origins of farming.

Keywords: Neolithic Revolution, economic growth, comparative development, biogeography, economic incentive, agricultural productivity

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).

This research investigates the biogeographical and economic origins of the Neolithic Revolution, both theoretically and empirically. It demonstrates that the human-driven extinction of large herbivores facilitated not only the independent emergence but also the diffusion of farming, with a particular emphasis on micro-regional and temporal variation. The analysis highlights the role of economic incentives as a key mechanism driving this transition. Moreover, it shows that once hunting resources were depleted, land suitability for agriculture played a critical role in the independent rise of farming. This finding underscores the role of economic incentives as a key mechanism, helps explain why pristine agriculture emerged only in limited regions, and contributes new insights to a literature that has often downplayed the importance of agricultural productivity in the origins of farming.

The model proposes mammalian biological traits that increase vulnerability to hunting pressure as deep parameters driving extinction. In the absence of secure property rights, individuals overexploit prey, leading to the extinction of species with such traits and a sharp decline in hunting yields. This decline creates economic incentives for foragers to begin cultivating wild plants, eventually resulting in domestication and, ultimately, the emergence and adoption of agriculture. The model also addresses a central puzzle of the Neolithic Revolution: Why did early humans adopt agriculture despite its higher labor demands and lack of immediate consumption benefits? While existing theories that highlight the advantages of farming over foraging fail to fully account for this shift, the extinction-based theory offers a reasonable explanation.

The empirical analyses test the proposed predictions using global panel data tracking $1^\circ \times 1^\circ$ grid cells over time, from 22,000 years before present until the onset of the Neolithic

¹For 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), Olsson and Paik (2016) and Dickens and Lagerlöf (2021), among others.

Revolution. For this purpose, I construct a measure of lost biomass as a proxy for the decline in hunting returns caused by extinction. This measure incorporates comprehensive information on the prehistoric global spatial distribution of all known mammal species since the Last Interglacial.² Because extinction is defined by the permanent loss of species, it generates variation in species presence over time. These spatial and temporal features of the underlying data make it possible to construct a granular measure of lost biomass across space and over time.

I use four complementary datasets on the Neolithic Revolution. Three document the timing and location of the diffusion of farming—one at the global country level and two at the archaeological site level for Europe, the Middle East, and East and Southwest Asia. In contrast, the fourth dataset identifies the well-established regions where pristine agriculture independently emerged. Together, these datasets allow for a comprehensive examination of the relationship between extinction and the Neolithic Revolution, leveraging distinct sources of variation and spatial coverage to uncover the effects of extinction on both the independent rise and the diffusion of agriculture.

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).³ 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 (Ashraf and Michalopoulos, 2015; Dow and Reed, 2023; Matranga, 2024), so controlling for these factors helps reduce concerns about spurious correlations.

Although the analyses control for a range of paleo-climatic and environmental variables as well as both time and cell fixed effects, one may still be concerned that unobserved factors such as local institutions or cultural practices could confound the relationship between extinction and the Neolithic Revolution. To address this concern, I employ an instrumental variable (IV) approach, leveraging the theoretical prediction derived from the model. The instrument replaces the *actual* extinction status with a *predicted* extinction probability derived from plausibly exogenous biological traits associated with extinction risk. Specifically, I use species’ digestive systems as the key trait. Digestive systems influence how frequently mammals need to feed, thereby affecting their exposure to hunters. As a result, species with

²The 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).

³Recent 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).

less efficient digestive systems are more likely to go extinct, conditional on other reproductive traits and paleo-climatic and environmental conditions. Crucially, digestive systems evolved well before the emergence of humans, making them plausibly exogenous.

The empirical analysis first demonstrates a global cross-country correlation between the spread of agriculture and lost biomass aggregated to this level. While cross-country data on the Neolithic Revolution raise concerns regarding measurement and endogeneity,⁴ they offer the broadest spatial coverage of farming spread, thereby showing that the proposed link between extinction and the diffusion of agriculture holds at a global scale. Although the cross-country analysis does not claim any causality, the association remains robust to controls for a wide range of paleo-climatic and environmental variables, geographical features, and continent fixed effects. Furthermore, the results remain stable when individual continents are sequentially excluded.

Then, I turn to granular grid-cell panel analyses to examine the effects of lost biomass on both the diffusion and independent emergence of farming. Using $1^\circ \times 1^\circ$ grid-cell panel data linked to archaeological evidence from Europe, the Middle East, and parts of Asia, the analysis shows that cells experiencing greater loss of biomass due to human-driven extinction were more likely to adopt agriculture from neighboring regions. Importantly, this pattern also holds when using global data on the independent rise of pristine agriculture: grid cells with greater lost biomass are significantly more likely to witness the independent emergence of farming. These panel analyses control for an extensive set of paleo-climatic and environmental characteristics, as well as cell and time fixed effects, thereby addressing major sources of confounding. Furthermore, the results remain robust when applying the IV approach that exploits variation in digestive systems as an exogenous source of biological vulnerability to hunting pressure.

Furthermore, I provide evidence that economic incentives were a key mechanism driving the transition to farming. Specifically, I examine whether the effect of lost biomass varies with land suitability for agriculture. The rationale is straightforward: higher land suitability increases potential agricultural yields, thereby strengthening the economic incentive for foragers experiencing severe extinction to adopt farming. Consistent with this prediction, the grid-cell panel estimates show that the positive effect of lost biomass on the likelihood of pristine agriculture is significantly larger in areas with higher land suitability.

This research contributes to several strands of social science literature. It relates to the

⁴Modern national borders are irrelevant to the adoption of agriculture in (pre)historical times. Moreover, the cross-country approach cannot account for potential confounders arising from country-specific time-varying factors, time-invariant characteristics within countries, or time-varying influences shared across countries.

broad literature on the origins of the Neolithic Revolution.⁵ Diamond (1997) argues that the availability of domesticable mammal and plant species was a primary driver of the rise of farming. Several scholars emphasize climatic factors, such as intergenerational temperature volatility (Ashraf and Michalopoulos, 2015), climatic reversal (Dow and Reed, 2023), and climatic seasonality (Matranga, 2024). The agricultural transition has also been linked to the coevolution of farming and private property rights (Bowles and Choi, 2019), species diversity of mammals, birds, and amphibians (Gershman and Morihara, 2022), and human characteristics (Grall et al., 2024).

My contribution to this broad literature is threefold. First, I provide the first empirical evidence that human-driven extinction of large herbivores spurred both the independent emergence and the diffusion of agriculture at *micro-regional* scales and *over time*. Second, I address two longstanding puzzles in the literature. Theoretically, I develop an extinction-based framework that explains why early farmers adopted agriculture despite its initially higher labor demands and the absence of immediate consumption gains. Empirically, I show that land suitability for agriculture was a critical factor in the rise of pristine agriculture—a dimension largely overlooked by existing studies. In his influential book *Guns, Germs, and Steel* (1997) and subsequent work (Diamond, 2002), Jared Diamond argues that agricultural productivity of land did not matter for the initial emergence of farming. In contrast, I find that it did matter in the context of large-herbivore extinction: regions with higher agricultural suitability were more likely to transition to farming when they had experienced substantial losses of hunting resources. Third, this heterogeneity in agricultural suitability also helps explain why pristine agriculture emerged in only a few regions. As Dow and Reed (2023) emphasize, any competing theory of the rise of farming must account for this fact. While most existing studies do not provide such an explanation, my findings offer a plausible one: because regions that simultaneously combined high land suitability for agriculture with severe large-herbivore extinction were relatively rare, the number of locations where pristine agriculture could originate was inherently constrained.

Within the literature on the origins of the Neolithic Revolution, this study relates to a key strand that links the reduction of foraging resources to the transition to farming. The Broad Spectrum Revolution (BSR) hypothesis, prominent in archaeology, anthropology, and evolutionary biology (Flannery, 1969; Stiner, 2001; Spengler et al., 2021), posits that the decline of large prey and increasing population pressure pushed foragers to diversify their diets, thereby paving the way for early cultivation and agriculture. Smith (1975)

⁵The origins of agriculture have been widely debated across disciplines including economics, archaeology, anthropology, and evolutionary biology. A comprehensive review is beyond the scope of this paper. For detailed overviews, see Weisdorf (2005) and Price and Bar-Yosef (2011).

theoretically connects population pressure and hunting efficiency to the overexploitation of prey, suggesting that resource depletion contributed to the agricultural transition in the Americas. More recently, Riahi (2020; 2024) proposes a theory that explains large-regional (e.g., continental) differences in the likelihood of pristine agriculture by linking megafauna extinction across Africa, the Americas, and Eurasia to macroevolutionary interactions among humans, plants, animals, ecology, institutions, and culture. Using present-day cross-country data, he empirically finds a hump-shaped relationship between megafauna extinction and the likelihood of pristine agriculture, drawing economists' attention to the possibility that variation in mammal extinction across large regions influenced the Neolithic transition and long-run development patterns at that scale.

My contribution to this important strand of the literature on the origins of the Neolithic Revolution is twofold. First, while the BSR hypothesis assumes that the decline of large game initiated the transition to farming, I provide direct empirical evidence supporting this claim by using micro-regional and temporal variation. Moreover, whereas the BSR literature has largely relied on regional archaeological case studies, my study offers global empirical evidence, demonstrating that the local patterns identified in prior work reflect a broader, worldwide phenomenon. Second, I advance a new theory and provide supporting empirical evidence that complement existing studies (Riahi, 2020; 2024) (see Online Appendix C for a detailed comparison). His macroevolutionary theory demonstrates a hump-shaped relationship between extinction and the independent rise of farming at macro-regional scales. His result, however, raises important questions about how extinction affected the Neolithic Revolution at finer spatial and temporal levels and through what mechanisms in such contexts. My study addresses these questions. I develop a model based on *economic incentives* predicting a *linear* and *positive* effect of extinction on both the *emergence* and *spread* of agriculture at *micro-regional* scales *over time*. Consistent with this distinction, $1^\circ \times 1^\circ$ grid-cell analyses show no hump-shaped relationship using Riahi's extinction measure, whereas my lost biomass measure remains a strong linear predictor.⁶ Overall, these findings suggest that the impact of extinction on the Neolithic Revolution may depend on spatial scale and the inclusion of time variation.

Lastly, and importantly, this research also relates to the literature on comparative development and persistence studies (see Voth (2021) for a review), which seeks to explain contemporary differences in income, institutions, and culture through historical factors such as (bio)geography, human traits, and historical events. A seminal contribution by Diamond (1997) argues that the timing of the Neolithic Revolution laid the foundations for divergent socio-economic trajectories, thereby shaping contemporary variation in prosperity across

⁶This difference reflects the distinct scope of our conceptual frameworks rather than a contradiction.

continental scales. Olsson and Hibbs Jr (2005) empirically support this view, showing that biogeographic conditions influenced today’s economic development and institutions through their impact on the timing of agricultural transitions. Borcan et al. (2018) provide evidence that state formation followed the adoption of agriculture globally, implying that agricultural transition was a prerequisite for subsequent societal development. Mayshar et al. (2022) find that, following the Neolithic transition, the cultivation of highly appropriable crops facilitated the emergence of hierarchical societies. Finally, Link (2024) show that the domestication of transport mammals fostered long-distance trade and the emergence of social hierarchies.

My contribution to the literature on comparative development and persistence studies is threefold. First, I introduce several novel datasets on prehistoric mammalian species and develop a new measure of hunting-resource loss from extinction, together with an instrumental variable. Both are available at various spatial scales and in cross-sectional and panel formats, covering the entire world from deep prehistory to the present. These tools enable researchers to quantify hunting-resource loss and approximate the causal effect of extinction across diverse spatial and temporal scales, regardless of their region of interest. Second, using these data and measures, I provide robust empirical evidence that human-driven megaherbivore extinction was a key driver of the global emergence and diffusion of farming. Third, I suggest that the impact of mammal extinction on the Neolithic Revolution may depend on the spatial scale of analysis and the inclusion of temporal variation, offering a new perspective to the literature that often treats the effects of deep-rooted factors as fixed across space and time. This study provides one of the most comprehensive analyses to date of the origins of the Neolithic Revolution, presenting systematic evidence that both extinction dynamics and economic incentives shaped the emergence and diffusion of farming. It suggests that, insofar as the Neolithic transition influenced subsequent socioeconomic development, prehistoric extinctions may have left enduring imprints on social, political, and economic outcomes.

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. Online Appendices A provides prehistorical evidence.

2 The Model

This section presents a model of the transition from hunting to farming, emphasizing economic incentives as the central mechanism. It highlights the role of large herbivore extinction in driving this transition, with the biological vulnerability of prey species identified as

a fundamental determinant of their extinction. The theory includes Malthusian pressure, making population growth an internal factor. It provides a reasonable 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.⁷ 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 gains of the two sectors. Online Appendix B presents a model that includes gathering as an additional production mode, yielding the same testable predictions as the basic model.

2.1 Production of Final Output

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

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

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 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:

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

In the agricultural sector, land was abundant during the transition, leading to constant

⁷The 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).

⁸Hart (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.

returns to labor.⁹ The output at time t , Y_t^a , is:

$$Y_t^a = A_t^a X^a L_t^a, \quad (3)$$

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:

$$y_t^a = A_t^a X^a. \quad (4)$$

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 and Reed, 2023).^{10, 11} Hence, growth of agricultural technology is modeled as

$$A_{t+1}^a = F(A_t^a, L_t^a), \quad (5)$$

where $A_{t+1}^a = F(A_t^a, L_t^a) = A_t^a$ if $L_t^a = 0$, and $\partial F(A_t^a, L_t^a)/\partial L_t^a > 0$ if $L_t^a > 0$. 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 (Koch and Barnosky, 2006). Hence, the law of evolution of biomass is

$$B_{t+1} = \begin{cases} B_t + \kappa(v)(\bar{B} - B_t) - A^h B_t^\alpha (L_t^h)^{1-\alpha} & \text{if } B_t > B^*(v) \\ B_t - A^h B_t^\alpha (L_t^h)^{1-\alpha} & \text{if } B_t \leq B^*(v), \end{cases} \quad (6)$$

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

¹⁰Dow and Reed (2023) likewise do not assume technological progress in the foraging sector. They 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.

¹¹While incorporating the evolution of hunting productivity increases the model's complexity, it does not alter the qualitative results as long as technological progress in agriculture outpaces that in hunting. Given that humans spent over 95% of their history as foragers, and that the period under analysis corresponds to the transition from foraging to farming—a final phase of this long foraging history—it is reasonable to assume that the hunting sector had reached a steady-state level of technology with little further advancement.

where κ is the rate of replenishment, \bar{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 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.¹² 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 assume¹³

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

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

¹²These are, for example, longer gestation periods, longer maternal care periods, older age at sexual maturity, and inefficient digestive systems

¹³To derive testable predictions from the argument below, only one of the two conditions needs to hold; therefore, dropping either does not affect the theoretical results.

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

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

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

$$c_t \leq y_t(1 - pn_t - l_t), \quad (9)$$

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

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

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 $y_t \geq \tilde{c}$,

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

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.

Since prehistoric economies operated under the Malthusian mechanism, where subsistence constraints were binding and the income elasticity of demand for children was positive, I assume:

$$\tilde{c} \leq y_t \leq \tilde{y}. \quad (12)$$

2.5 Evolution of the Population

The evolution of the working population over time is

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

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

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

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

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

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 $y^h(B_t, L_t; A^h) > y^a(A_t^a, X^a)$,*

$$L_{t+1} \begin{matrix} \geq \\ \leq \end{matrix} L_t \Leftrightarrow L_t \begin{matrix} \leq \\ \geq \end{matrix} L_t^{LL}. \quad (16)$$

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

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

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:

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

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 $B_t > B^*$,*

$$B_{t+1} \begin{matrix} \geq \\ \leq \end{matrix} B_t \Leftrightarrow B_t \begin{matrix} \leq \\ \geq \end{matrix} B_t^{BB}.$$

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

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

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

$$\frac{\partial L_t^{yy}}{\partial A_t^a} < 0. \quad (20)$$

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 ,*

$$y^h(B_t, L_t; A^h) \geq y^a(A_t^a, X^a) \Leftrightarrow L_t \leq L_t^{yy}. \quad (21)$$

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 ,*

$$y^h(B_t^{LL}, L_t^{LL}; A^h) \geq y^a(A_t^a, X^a) \Leftrightarrow L_t^{yy} \geq L_t^{LL} \Leftrightarrow n[y^a(A_t^a, X^a)] \leq 1. \quad (22)$$

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 Neolithic Revolution

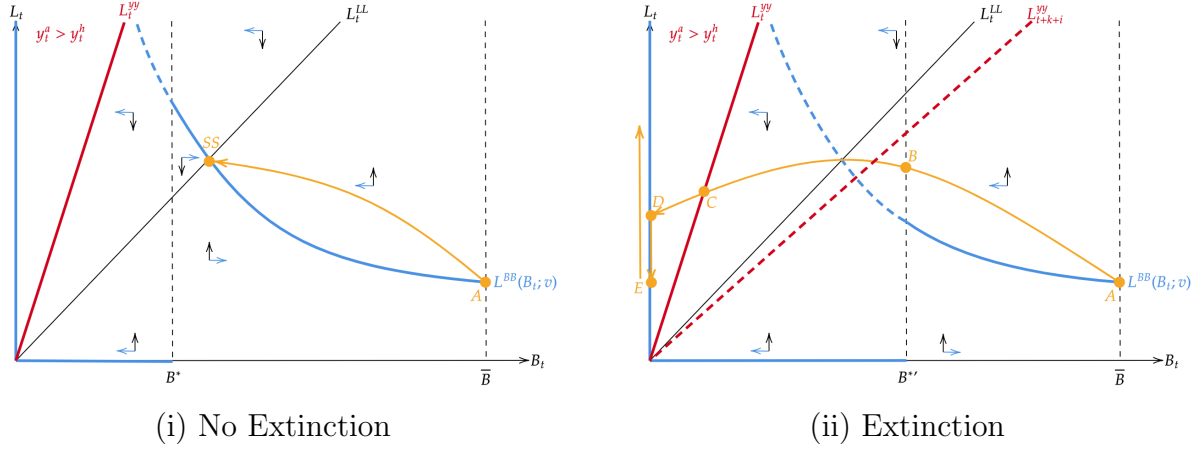


Figure 1: The Effect of Extinction

Figure 1 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 \bar{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 $B_0 = \bar{B}$. 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.¹⁴ Ultimately, agriculture becomes the dominant subsistence strategy.¹⁵

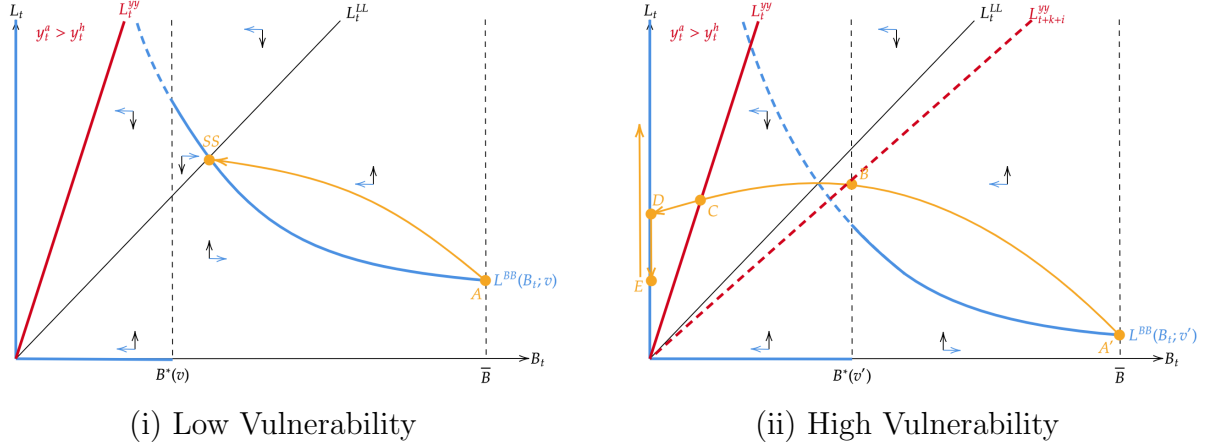


Figure 2: The Effect of Biological Vulnerability

2.7.2 The Effect of Biological Vulnerability on the Neolithic Revolution

Figure 2 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

- (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.*

¹⁴Agricultural 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 (6).

¹⁵Without agricultural progress, the economy would converge to a steady state with zero biomass and population.

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.

Online Appendix B extends the basic model by incorporating the gathering sector, without altering the model’s predictions. 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). 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 leisure¹⁶, declining incomes forced early farmers to work harder despite no immediate increase in food availability.

3 Data and Variable Construction

This section describes the main datasets used in the analysis, with a particular focus on newly constructed data on prehistoric mammals and paleoclimate. It also explains the construction of the key independent variable—biomass loss due to mammal extinction—and the instrument for it, which is based on biological traits associated with vulnerability to hunting pressure.

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 E1 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 agricultural diffusion, they are a

¹⁶This characteristic is derived in (11). Sahlins (1972) provides examples and illustrates the relationship between food gains and work time in foraging societies, supporting this argument.

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).¹⁷ 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). Following Grall et al. (2024), I combine these datasets for empirical analysis.¹⁸ Figure E2 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.

These datasets include information on both the independent transition to domestication and its subsequent spread, with the latter comprising the majority of observations. To capture the association between megaherbivore extinction and the independent emergence of agriculture rather than its diffusion, I also exploit information on independent centers of plant domestication as reported by Larson et al. (2014). Relying on genetic, molecular, and archaeological research, they provide global information on places and timing of independent plant domestication.

3.2 Independent Variable: Lost Biomass

This subsection introduces a measure of lost biomass from megaherbivore extinction, constructed at multiple spatial scales—including country, archaeological site, grid cell, and ethnic homeland—and applicable in both cross-sectional and panel analyses. 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) and Faurby et al. (2020), provides spatial distribution data for 5,831 known mammal species that have lived since the Late Pleistocene (about 130,000 years ago to present).¹⁹ 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

¹⁷Data 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.

¹⁸However, I also test robustness using each dataset separately. The results remain consistent with those obtained from the combined dataset.

¹⁹This database is used in economics by Kumagai (2021; 2024) and Link (2024).

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).²⁰ To calculate population density, and therefore abundance, I apply the regression from Silva and Downing (1995): $\log_{10}(\text{Population Density}) = -0.44 \log_{10}(\text{Body Mass}) + 1.01$.²¹

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:

$$\text{LostBiomass}_i = \frac{\sum_{j \in MH_i^{\text{extinct}}} \widehat{\text{Abundance}}_j \times \text{BodyMass}_j}{\sum_{j \in MH_i} \widehat{\text{Abundance}}_j \times \text{BodyMass}_j}, \quad (23)$$

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 , $\widehat{\text{Abundance}}_j$ represents the estimated number of individuals for species j , and BodyMass_j is the average body mass of species j .^{22,23}

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

$$\text{LostBiomass}_{i,t} = \frac{\sum_{j \in MH_{i,t}^{\text{extinct}}} \widehat{\text{Abundance}}_j \times \text{BodyMass}_j}{\sum_{j \in MH_{i,t}} \widehat{\text{Abundance}}_j \times \text{BodyMass}_j}, \quad (24)$$

where $MH_{i,t}^{\text{extinct}}$ is the set of mammals that become extinct between time t and $t - 1$ in

²⁰This method is commonly used in paleoecology to estimate prehistoric species abundance (Byers and Ugan, 2005; Barnosky, 2008 among others).

²¹The 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.

²²This 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.

²³Species extinct after the first Neolithic transition are excluded to reduce concerns of reverse causality.

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

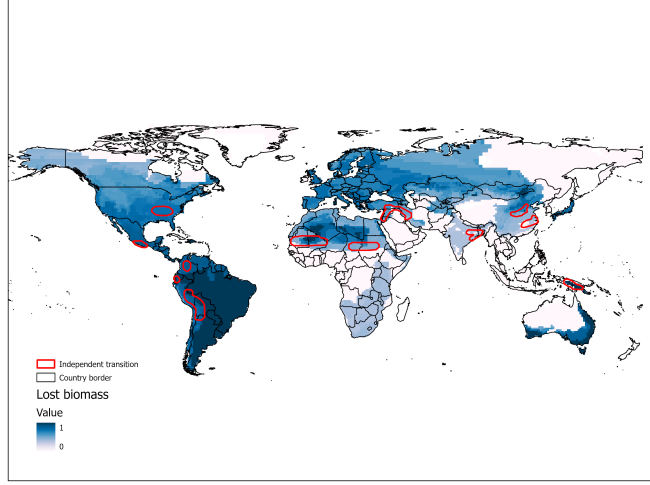


Figure 3: Lost biomass and places of independent Neolithic transition

The global distribution of lost biomass due to megaherbivore extinction is depicted in Figure 3. 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.

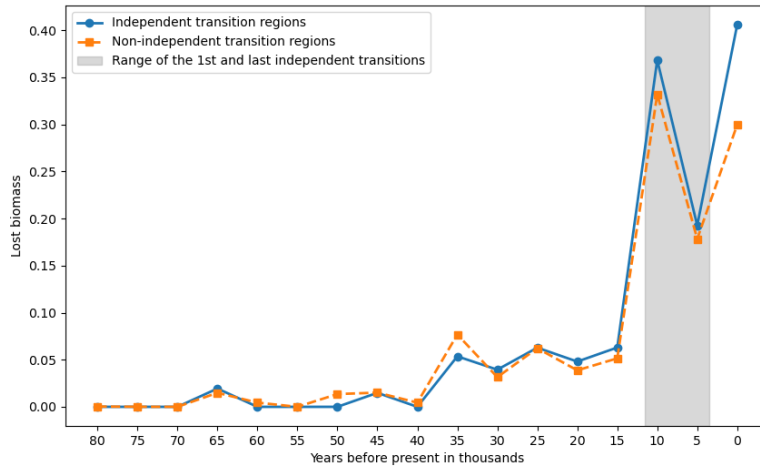


Figure 4: Evolution of lost biomass

Figure 4 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.

This measure of lost biomass is effective if it accurately reflects past hunting potential. 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 not significant or negative, if any. Additionally, Table F4, 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 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).²⁴ 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 (Ashraf and Michalopoulos, 2015; Dow and Reed, 2023; 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 dataset from Beyer et al. (2020), which provides bias-corrected, high-resolution (0.5°) global climatic data covering the past 120,000 years, with a temporal resolution of 1,000–2,000 years. From this dataset, I compute the means and standard deviations of paleo-temperature, paleo-precipitation, and paleo-net primary productivity. Paleo-net primary productivity is used as a proxy for ecosystem productivity (Rosenzweig et al., 2012) to account for potential systematic differences in ecosystems that may have influenced megaherbivore extinction and the agricultural transition. In addition, I calculate paleo-ecological diversity, as ecological diversity may have shaped mammalian niches and influenced human subsistence strategies through the availability of diverse biomes.

²⁴Recent 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).

3.4 Instrumental Variable: Predicted Probability of Extinction

In the baseline analysis, I control for cell and time fixed effects as well as paleo-climatic and environmental conditions, which represent the most important confounders in prehistoric contexts. However, one may still concern that unobserved factors such as the evolution of local institutions and culture could bias the estimated relationship between extinction and the Neolithic Revolution.^{25,26}

The theoretical model predicts that biological vulnerability increases extinction risk and influences the Neolithic transition, thereby motivating the use of such traits as an instrumental variable. To construct the instrument, I focus on a specific biological trait: digestive systems. 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 determines how long herbivores spend feeding and, consequently, their exposure to hunters. Digestive efficiency depends on food retention time in the gastrointestinal tract: longer retention allows for greater fermentation and nutrient absorption. Hindgut fermenters digest food quickly, requiring more frequent feeding and extended foraging, which increases predation risk. Foregut non-ruminants are more efficient because food is retained longer, but they remain less efficient than foregut ruminants, whose specialized digestive systems maximize energy extraction. By spending less time feeding, foregut ruminants reduce their exposure to hunters, making them the most efficient herbivores at avoiding predation. Accordingly, studies widely regard hindgut fermenters as the most vulnerable to hunting, followed by foregut non-ruminants and, least vulnerable, foregut ruminants (Janis, 1976; Van Soest, 1996; Owen-Smith, 2002; Godoy-Vitorino et al., 2012).

The *Herbitraits* database (Lundgren et al., 2021) provides information on the diges-

²⁵The main panel analyses are conducted at the granular level of $1^\circ \times 1^\circ$ grid cells and control for time-varying paleo-climatic conditions, as well as both time and cell fixed effects. Given the slow pace of institutional and cultural change, these controls are likely to absorb a substantial portion of potential confounding. However, to the extent that the long time horizon of the analysis introduces meaningful variation, concerns about endogeneity may still be warranted.

²⁶For example, Bowles and Choi (2019) argue that some foraging societies developed private property rights, which facilitated the Neolithic Revolution. The presence of such rights could have mitigated the tragedy of the commons—reducing overhunting and, consequently, biomass loss. Cultural traits among foraging societies may have influenced both agricultural adoption and extinction patterns. For instance, long-term orientation may have promoted investment in agriculture (Galor and Özak, 2016) while discouraging overhunting. Additionally, measurement error in the data may introduce bias. These factors likely bias the OLS estimate downward. In such cases, the OLS estimate is likely to be downward biased.

tive efficiency of all late Quaternary mammalian herbivores over 10 kg. Its ranking system—hindgut fermenters (1), foregut non-ruminants (2), and foregut ruminants (3)—reflects increasing digestive efficiency and is fully consistent with the standard understanding in the zoological and ecological literature. For my analysis, I reverse this scale to construct an index of digestive inefficiency, such that higher values indicate lower digestive efficiency.

Importantly, the digestive systems I use in this analysis evolved long before anatomically modern humans appeared in East Africa around 300,000 years ago. For instance, 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 presence, meaning the traits I use for constructing the instrumental variable are plausibly *pre-determined* by the time humans emerged.

I construct the instrument as follows. First, I regress the actual extinction status on digestive inefficiency using the *logistic* model, controlling for palae-climatic and environmental characteristics and body mass (*First Step*). Table F5 shows that digestive inefficiency positively and significantly predict extinction. Second, I calculate the predicted extinction probability using the coefficients of digestive inefficiency estimated in the first step (*Second step*). This estimated coefficient allows 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:

$$\widehat{LostBiomass}_i = \frac{\sum_{j \in MH_i} \widehat{\mathbb{1}_{j \in \text{Extinct}}} \times \widehat{Abundance}_j \times \widehat{BodyMass}_j}{\sum_{j \in MH_i} \widehat{Abundance}_j \times \widehat{BodyMass}_j}. \quad (25)$$

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

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

where $\widehat{Biomass}_j$ is the product of $\widehat{Abundance}_j$ and $\widehat{BodyMass}_j$, and $\#(T)$ represents the number of sample periods in the panel. Thus, $\widehat{\mathbb{1}_{j \in \text{Extinct}}}/\#(T)$ and $1 - \widehat{\mathbb{1}_{j \in \text{Extinct}}}/\#(T)$ in-

icate 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.

It is worth mentioning that I address several potential concerns regarding the validity of the proposed instrument. First, environmental factors may have influenced extinction risk. To address this, I control directly for paleo-climatic and environmental characteristics. Second, one might argue that using digestive inefficiency as an instrument involves a category error, as the persistence of multiple digestive strategies likely reflects ecological trade-offs. I partially address this by controlling for paleo-ecological diversity, which captures variation in ecological niches across regions.²⁷ Third, I exclude domesticable species from the sample to avoid the concern that digestive traits may be directly related to domestication potential. Fourth, I control for body mass to address the concern that other biological traits correlated with extinction risk may confound the relationship. Body size is known to be correlated with key reproductive traits, including gestation length, maternal care duration, age at sexual maturity, birth rate, genetic variability, among others (McDonald, 1984; Wooten and Smith, 1985; Smith, 1975, 1992; Johnson, 2002; Brook and Bowman, 2004). Controlling for body size thus helps isolate the effect of digestive inefficiency from other biological characteristics that affect reproductive success and, in turn, extinction risk.

4 Empirical Evidence

This section presents empirical evidence that megaherbivore extinction positively influenced the Neolithic Revolution, using a range of complementary datasets. I begin with a cross-country analysis, without making causal claims, to illustrate the global correlation between extinction and the spread of agriculture. I then turn to $1^\circ \times 1^\circ$ grid-cell panel analyses, which allow for the inclusion of time-varying paleo-climatic and environmental conditions as well as time and cell fixed effects. The first of these uses archaeological site data, providing precise information on human settlements and thus enabling a more accurate measurement of agricultural diffusion. To examine the effect of extinction on independent agricultural

²⁷Related to the second point, hindgut fermenters may have been more efficient in environments with patchy forage, as they can process large quantities of plant matter quickly. In such settings, where rapid consumption and frequent movement may be advantageous, hindgut foragers may have held a relative advantage. To address this, I control for both the mean and standard deviation of paleo-net primary productivity. As net primary productivity proxies for overall ecosystem productivity and herbivore food availability (Rosenzweig et al., 2012), including these controls helps mitigate this concern.

origins, I then employ a panel of grid cells where farming developed independently.

This section further addresses unresolved questions in the literature. First, the established linear positive effect at the micro-regional scale and over time complements the quadratic relationship identified by Riahi (2020; 2024), who analyzes cross- and macro-regional variation. Second, it explores heterogeneity by land suitability for agriculture, showing that regions experiencing both severe extinction and high agricultural productivity were more likely to witness the independent rise of farming. Together, these findings highlight (i) the scale-dependent impacts of extinction when spatial and temporal variation are considered, (ii) the central role of economic incentives, (iii) the rarity of regions conducive to pristine agricultural origins, and (iv) the importance of agricultural land productivity for the emergence of early farming.

4.1 Cross-Country Correlation

This subsection briefly presents the global correlation between megaherbivore extinction and the timing of the Neolithic transition at the country level.²⁸ Summary statistics are provided in Table F1. The association is estimated using the following specification:

$$YST_i = \alpha_0 + \alpha_1 LostBiomass_i + PaleoFactors_i \beta' + Geo_i \gamma' + Continent_i \delta' + \epsilon_i, \quad (27)$$

where YST_i represents the time elapsed since the Neolithic transition in country i , $LostBiomass_i$ is the loss of biomass due to megaherbivore extinction in country i , $PaleoFactors_i$ is a vector of paleoclimatic and environmental 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 relationship between lost biomass and the time since the agricultural transition, meaning $\alpha_1 > 0$.

Table 1 confirms a positive association between lost biomass and the timing of the Neolithic transition. Columns 1–5 include all available countries. Columns 1–4 sequentially control for paleo-climatic factors, paleo-net primary productivity, and paleo-ecological diversity, while Column 5 additionally includes geographic characteristics: log distance to the nearest center of agricultural origin, absolute latitude, the mean and standard deviation of land suitability for agriculture, terrain ruggedness, land area, and log distance to the nearest waterway. Notably, the estimated coefficients on lost biomass remain stable and highly

²⁸As the primary purpose of this analysis is to demonstrate a global correlation consistent with the proposed hypothesis, I do not report robustness checks for the cross-country analysis here just in order to save space. However, as shown in an earlier version of the working paper, the main findings are robust to a variety of sensitive tests. These robustness checks can be found in the previous draft or are available upon request.

Table 1: Correlation between lost biomass and the Neolithic Revolution across countries

	Years elapsed since the NR (in 100 years)									
	(1) Entire world	(2) Entire world	(3) Entire world	(4) Entire world	(5) Entire world	(6) No Africa	(7) No Americas	(8) No Asia	(9) No Europe	(10) No Oceania
Lost biomass	0.40*** (0.10)	0.41*** (0.09)	0.43*** (0.10)	0.39*** (0.11)	0.35*** (0.11)	0.31** (0.12)	0.41*** (0.12)	0.33** (0.13)	0.38*** (0.12)	0.34*** (0.10)
Paleo-temperature (mean)		0.37*** (0.07)	0.58*** (0.09)	0.68*** (0.07)	0.57*** (0.12)	0.78*** (0.15)	0.64*** (0.13)	0.56*** (0.18)	0.43*** (0.14)	0.57*** (0.12)
Paleo-precipitation (mean)		-0.22*** (0.06)	-0.10 (0.08)	-0.18 (0.12)	-0.23** (0.10)	-0.50*** (0.15)	-0.26** (0.10)	-0.15 (0.11)	-0.11 (0.12)	-0.23** (0.10)
Paleo-temperature (std.)			0.25*** (0.05)	0.33*** (0.06)	0.30*** (0.06)	0.25*** (0.07)	0.31*** (0.07)	0.35*** (0.09)	0.25*** (0.07)	0.28*** (0.06)
Paleo-precipitation (std.)			-0.18*** (0.06)	0.02 (0.09)	-0.03 (0.07)	0.21** (0.09)	-0.10 (0.07)	0.05 (0.09)	-0.10 (0.08)	-0.06 (0.07)
Paleo-net primary productivity (mean)				0.10 (0.13)	0.12 (0.14)	0.27 (0.18)	0.20 (0.14)	0.18 (0.16)	0.03 (0.18)	0.06 (0.14)
Paleo-net primary productivity (std.)				-0.36*** (0.09)	-0.41*** (0.09)	-0.46*** (0.10)	-0.45*** (0.09)	-0.31*** (0.11)	-0.29*** (0.09)	-0.38*** (0.09)
Paloe-ecological diversity				0.01 (0.06)	-0.05 (0.07)	-0.05 (0.07)	0.01 (0.08)	-0.11 (0.10)	-0.15* (0.08)	-0.04 (0.07)
Outcome mean	49.08	49.08	49.08	49.08	49.08	57.11	52.72	40.12	45.74	49.47
Continent FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Geographical controls					✓	✓	✓	✓	✓	✓
Adjusted R^2	0.66	0.73	0.76	0.79	0.84	0.83	0.86	0.78	0.84	0.84
Observations	143	143	143	143	143	100	118	102	111	141

Note: The unit of analysis is the country. Columns 1–5 include all countries, while Columns 6–10 sequentially exclude countries from Africa, the Americas, Asia, Europe, and Oceania, respectively. Continent fixed effects include Africa, the Americas, Asia, Europe, and Oceania. Geographic controls comprise the log distance to the nearest center of agricultural origin, absolute latitude, the mean and standard deviation of land suitability for agriculture, terrain ruggedness, land area, and the log distance to the nearest waterway. All variables are standardized. Robust standard errors are reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

statistically significant across all specifications.

Columns 6–10 sequentially exclude countries from one continent at a time. As shown in these columns, the estimates are not driven by any single continent; both the magnitude and precision of the coefficients remain remarkably consistent with those obtained using the full sample. The estimates are also economically meaningful: a one-standard-deviation increase in lost biomass is associated with a 0.35 standard deviation increase in the years elapsed since the agricultural transition. Given that the standard deviation of the dependent variable is 23.5, this corresponds to approximately 824 years. This finding underscores that the correlation between lost biomass and the Neolithic transition is a globally observed pattern.

4.2 Archaeological Site Panel Analysis

This subsection examines 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 begin by constructing a grid of $1^\circ \times 1^\circ$ cells and assigning each archaeological site to its corresponding cell. For each grid cell, I calculate the transition timing by averaging the dates of the sites located within it. Using this grid-cell structure, I build a panel dataset that incorporates information on lost biomass and paleo-climatic and environmental conditions.²⁹ Summary statistics are presented in Table F2.

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

$$\mathbb{1}_{i,t} = \alpha_0 + \alpha_1 \text{LostBiomass}_{i,t-1} + \text{PaleoFactors}_{i,t-1} \beta' + \text{Cell}_i \gamma' + \text{Time}_t \delta' + \epsilon_{i,t}, \quad (28)$$

where $\mathbb{1}_{i,t}$ is a dummy variable that indicates whether agricultural transition occurs in cell i at period t , $\text{LostBiomass}_{i,t-1}$ is loss of biomass caused by megaherbivore extinction in cell i in period $t - 1$, $\text{PaleoFactors}_{i,t-1}$ is a vector of paleo-climatic and environmental variables 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 22,000 BP until the transition occurs, with each time window representing 1,000 years.³⁰ I use a one-period lag of the independent variables to address

²⁹I also conduct robustness checks by analyzing each dataset (Pinhasi et al., 2005; Cobo et al., 2019) separately and report the results accordingly.

³⁰Paleo-climate data from Beyer et al. (2020) is available in 1,000-year intervals from 22,000 BP onward. For earlier periods, data is only available in 2,000-year intervals. Therefore, I restrict the sample to 22,000 BP onward and employ 1,000-year time windows.

concerns about reverse causality.

Table 2: Basic result and placebo test (archaeological site panel)

	Neolithic Revolution indicator									
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS	(9) OLS	(10) OLS
Lost biomass (t-1)	0.093*** (0.019)	0.089*** (0.019)	0.089*** (0.019)	0.085*** (0.019)	0.085*** (0.019)					
Lost biomass (t+1)						0.003 (0.019)	-0.007 (0.019)	-0.009 (0.019)	-0.009 (0.019)	-0.009 (0.019)
Paleo-temperature (mean) (t-1)		0.341*** (0.081)	0.442*** (0.088)	0.666*** (0.090)	0.667*** (0.090)		0.368*** (0.084)	0.468*** (0.091)	0.694*** (0.091)	0.695*** (0.091)
Paleo-precipitation (mean) (t-1)		-0.556*** (0.062)	-0.591*** (0.064)	-0.348*** (0.072)	-0.348*** (0.072)		-0.551*** (0.062)	-0.586*** (0.065)	-0.340*** (0.073)	-0.340*** (0.073)
Paleo-temperature (std.) (t-1)			0.180** (0.078)	0.093 (0.078)	0.092 (0.078)			0.174** (0.078)	0.087 (0.079)	0.087 (0.079)
Paleo-precipitation (std.) (t-1)			0.131*** (0.050)	0.093* (0.050)	0.094* (0.050)			0.133*** (0.051)	0.095* (0.052)	0.095* (0.052)
Paleo-net primary productivity (mean) (t-1)				-0.481*** (0.070)	-0.481*** (0.070)				-0.488*** (0.071)	-0.488*** (0.070)
Paleo-net primary productivity (std.) (t-1)				-0.070** (0.027)	-0.067** (0.028)				-0.072*** (0.027)	-0.070** (0.028)
Paleo-ecological diversity (t-1)					-0.009 (0.021)					-0.006 (0.022)
Outcome mean	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Adjusted R-Sqr.	0.297	0.312	0.313	0.320	0.320	0.289	0.304	0.305	0.312	0.312
Observations	7988	7988	7988	7988	7988	7978	7978	7978	7978	7978

Note: The unit of analysis is a $1^\circ \times 1^\circ$ grid cell. The dependent variable is an indicator equal to 1 if the grid cell undergoes an agricultural transition in a given period, and 0 otherwise. The panel spans from 22,000 BP until the transition occurs, using 1,000-year time intervals. 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 1-5 of Table 2 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 and stable, even when controlling for the means of paleo-temperature and paleo-precipitation (column 2), their standard deviations (column 3), the mean of paleo-net primary productivity, its standard deviation (column 4), and paleo-ecological diversity (column 5). By controlling for paleo-climatic characteristics, the estimated coefficient of lost biomass is better interpreted as human-driven and causal. The effect is economically meaningful: a one-standard-deviation increase in lost biomass is associated with a 0.085 standard deviation increase in the dependent variable, corresponding to approximately a 2 percentage point increase in the likelihood of agricultural transition.

Next, I replace the one-period lagged lost biomass with one-period ahead lost biomass in

equation (28). Columns 6-10 of Table 2 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.

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 F6 demonstrates that the results remain robust when using these different estimates.

Recalculated lost biomass including 14 domesticable mammals: Table F7 presents the results using recalculated lost biomass, now including the 14 domesticable mammal species. The table shows robustness to this exercise.

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. Tables F8 show robustness of the basic results to controlling for these dimensions of climates.

Splitting the sample into two datasets: To assess robustness, I split the basic sample into two subsamples based on Cobo et al. (2019) and Pinhasi et al. (2005). Table F9 restricts the sample to archaeological sites reported by Cobo et al. (2019). The results show a strong positive impact of lost biomass on the Neolithic transition. Table F10 presents the same analysis using the sample from Pinhasi et al. (2005). The results confirm a positive and significant relationship between lost biomass and the Neolithic transition, while controlling for 3,000-year time fixed effects instead of 1,000-year time fixed effects. This adjustment is necessary because, in this sample, 1,000-year or 2,000-year fixed effects explain a substantial portion of the variation in lost biomass and the Neolithic transition dummy. However, it should be noted that even using 3,000-year fixed effects represents a more demanding specification than previous studies based on Pinhasi et al. (2005), as those studies rely on a cross-sectional approach and do not account for any time fixed effects (and unit fixed effects).

Instrumental variable approach: Although the baseline OLS regressions control for an extensive set of paleo-climatic and environmental variables as well as time and grid-cell fixed effects, concerns may remain about unobserved time-varying confounders that could bias the estimates. To address this, I implement the 2SLS approach, instrumenting lost biomass with the predicted probability of extinction, as described in subsection 3.4. Table 3 reports the second-stage results (Panel A), first-stage estimates (Panel B), and reduced-form estimates

(Panel C). Across all specifications, the coefficients are statistically significant and remain stable. The estimated effect is also economically meaningful: a one percent increase in lost biomass is associated with approximately a 6.7 percentage point increase in the likelihood of transition.

Table 3: 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)	2.730*** (0.476)	2.495*** (0.542)	2.450*** (0.527)	2.571*** (0.515)								
Lost biomass (IV) (t-1)					4.506*** (0.750)	4.046*** (0.788)	4.186*** (0.801)	4.421*** (0.816)	12.301*** (2.034)	10.094*** (2.035)	10.257*** (2.034)	11.367*** (1.962)
Paleo-temperature (mean) (t-1)		-0.311 (0.201)	-0.123 (0.203)	-0.013 (0.231)		0.213*** (0.046)	0.171*** (0.051)	0.212*** (0.054)		0.222*** (0.085)	0.296*** (0.095)	0.533*** (0.101)
Paleo-precipitation (mean) (t-1)		-0.705*** (0.099)	-0.729*** (0.106)	-0.591*** (0.133)		0.075** (0.033)	0.069* (0.036)	0.122*** (0.043)		-0.517*** (0.069)	-0.560*** (0.071)	-0.278*** (0.080)
Paleo-temperature (std.) (t-1)			0.366*** (0.133)	0.312** (0.141)			-0.103** (0.049)	-0.121** (0.051)			0.112 (0.084)	0.002 (0.084)
Paleo-precipitation (std.) (t-1)			0.087 (0.076)	0.061 (0.080)			0.032 (0.032)	0.022 (0.034)			0.165*** (0.054)	0.118** (0.053)
Paleo-net primary productivity (mean) (t-1)				-0.293** (0.117)				-0.102*** (0.037)				-0.556*** (0.070)
Paleo-net primary productivity (std.) (t-1)				0.024 (0.049)				-0.028* (0.015)				-0.048* (0.029)
Paleo-ecological diversity (t-1)				-0.077 (0.048)				0.031* (0.016)				0.002 (0.021)
Outcome mean	0.059	0.059	0.059	0.059	0.019	0.019	0.019	0.019	0.059	0.059	0.059	0.059
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
First stage F	36.133	26.353	27.303	29.349								
Adjusted R-Sqr.					0.263	0.264	0.264	0.265	0.306	0.316	0.318	0.326
Observations	7988	7988	7988	7988	7988	7988	7988	7988	7988	7988	7988	7988

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 22,000 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. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

4.3 Independent Transition Grid Cell Panel Analysis

This subsection examines the impact of lost biomass on independent rise of farming using $1^\circ \times 1^\circ$ grid cell panel data. Larson et al. (2014) identify the well-established locations of independent plant domestication. First, I divide the earth into $1^\circ \times 1^\circ$ 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 5 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

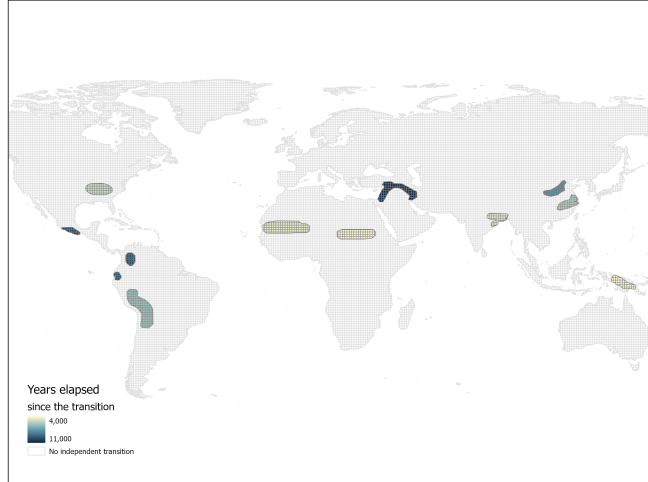


Figure 5: $1^\circ \times 1^\circ$ grid cell with the independent transition places

lost biomass and independent emergence of agriculture is estimated using equation (28).³¹ Summary statistics is found in Table F3

Columns 1–5 of Table 4 present a positive effect of lost biomass on the likelihood of pristine agriculture. All columns report OLS estimates and include both grid-cell and time fixed effects. The estimated coefficient for lost biomass remains highly robust, even after controlling for a comprehensive set of paleo-climatic and environmental variables. With these controls in place, the estimated effect can be more confidently interpreted as reflecting human-driven extinction and as being closer to causality. A one-standard-deviation increase in lost biomass is associated with a 0.017 standard deviation increase in the dependent variable, equivalent to approximately a 0.07 percentage point increase in the likelihood of pristine agriculture. Given that the mean and standard deviation of the dependent variable are 0.002 and 0.044, respectively, this effect is economically meaningful. Next, I replace the one-period lagged lost biomass with one-period ahead lost biomass in equation (28). Columns 6-10 of Table 4 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.

Overall, the estimates in Table 4 provide strong evidence that megaherbivore extinction contributed to the independent emergence of farming. The analysis includes time and grid-cell fixed effects, as well as a comprehensive set of paleo-climatic and environmental

³¹The limited variation in both the dependent and independent variables prevents nonlinear models (e.g., Probit) from converging once a number of cell and time fixed effects are included: the Neolithic Revolution indicator equals zero for more than 99% of the sample, and lost biomass equals zero for about 90%. Since these fixed effects are essential for the analysis, I rely on the linear probability model, which is more appropriate in this context. The same reasoning applies to the archaeological-site analysis in subsection 4.2.

Table 4: Basic result and placebo test (independent transition)

	Neolithic Revolution indicator									
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS	(9) OLS	(10) OLS
Lost biomass (t-1)	0.016*** (0.004)	0.017*** (0.004)	0.017*** (0.004)	0.017*** (0.004)	0.017*** (0.004)					
Lost biomass (t+1)							-0.017*** (0.002)	-0.017*** (0.002)	-0.017*** (0.002)	-0.017*** (0.002)
Paleo-temperature (mean) (t-1)		-0.269*** (0.016)	-0.260*** (0.016)	-0.267*** (0.017)	-0.266*** (0.016)		-0.271*** (0.016)	-0.261*** (0.016)	-0.268*** (0.017)	-0.266*** (0.017)
Paleo-precipitation (mean) (t-1)		0.051** (0.021)	0.044** (0.021)	0.022 (0.021)	0.023 (0.021)		0.041* (0.022)	0.033 (0.022)	0.013 (0.022)	0.014 (0.022)
Paleo-temperature (std.) (t-1)			0.022*** (0.004)	0.025*** (0.004)	0.026*** (0.004)			0.025*** (0.004)	0.028*** (0.004)	0.028*** (0.004)
Paleo-precipitation (std.) (t-1)			0.024** (0.011)	0.028** (0.012)	0.028** (0.012)			0.025** (0.011)	0.028** (0.012)	0.028** (0.012)
Paleo-net primary productivity (mean) (t-1)				0.041** (0.017)	0.041** (0.017)				0.038** (0.018)	0.038** (0.018)
Paleo-net primary productivity (std.) (t-1)				0.012 (0.007)	0.015* (0.008)				0.014* (0.008)	0.017** (0.008)
Paleo-ecological diversity (t-1)					-0.008* (0.004)					-0.008* (0.005)
Outcome mean	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Adjusted R-Sqr.	0.026	0.027	0.027	0.027	0.027	0.024	0.025	0.025	0.025	0.025
Observations	309926	309926	309926	309926	309926	294427	294427	294427	294427	294427

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 emergence of agriculture and 0 otherwise. The panel spans from 22,000 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. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

controls—addressing the most important confounding factors in this context.

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 F12 demonstrates that the results remain robust when using these different estimates.

Recalculated lost biomass including 14 domesticable mammals: Table F13 presents the results using recalculated lost biomass, now including the 14 domesticable mammal species. The table shows robustness to this exercise.

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. Tables F14 show robustness of the basic results to controlling for these dimensions of climates.

Instrumental variable approach: The baseline specification controls for numerous paleo-climatic and environmental factors, as well as cell and time fixed effects, which absorb many potential confounders. The results further remain robust when using a 2SLS approach that leverages digestive inefficiency as an exogenous source of variation in extinction risk. Table 5 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. Controlling for time and cell fixed effects and a number of paleo-climatic and environmental characteristics, this 2SLS results provide strong evidence of the impact of megaherbivore extinction on the likelihood of the independent agricultural transition.

Table 5: 2SLS, first stage, and reduced form (independent transition)

	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)	0.331*** (0.038)	0.294*** (0.037)	0.297*** (0.036)	0.301*** (0.036)								
Lost biomass (IV) (t-1)					4.012*** (0.134)	4.129*** (0.132)	4.163*** (0.132)	4.261*** (0.136)	1.326*** (0.151)	1.213*** (0.149)	1.236*** (0.149)	1.281*** (0.150)
Paleo-temperature (mean) (t-1)		-0.353*** (0.022)	-0.353*** (0.022)	-0.355*** (0.023)	0.321*** (0.013)	0.351*** (0.014)	0.333*** (0.014)		-0.259*** (0.015)	-0.249*** (0.015)	-0.255*** (0.015)	
Paleo-precipitation (mean) (t-1)		0.117*** (0.023)	0.113*** (0.023)	0.107*** (0.024)	-0.238*** (0.013)	-0.249*** (0.013)	-0.308*** (0.016)		0.047*** (0.021)	0.039*** (0.021)	0.014 (0.020)	
Paleo-temperature (std.) (t-1)			0.001 (0.006)	0.002 (0.006)		0.079*** (0.011)	0.088*** (0.011)			0.024*** (0.004)	0.029*** (0.004)	
Paleo-precipitation (std.) (t-1)			0.023** (0.011)	0.023** (0.012)		0.010 (0.007)	0.025*** (0.008)			0.026** (0.011)	0.031*** (0.012)	
Paleo-net primary productivity (mean) (t-1)				0.016 (0.017)				0.109*** (0.014)				0.049*** (0.017)
Paleo-net primary productivity (std.) (t-1)				0.011 (0.008)				0.015** (0.006)				0.016** (0.008)
Paleo-ecological diversity (t-1)				-0.011** (0.004)				0.010*** (0.003)				-0.008* (0.004)
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
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
First stage F	902.343	984.829	995.855	986.300								
Adjusted R-Sqr.					0.210	0.212	0.212	0.212	0.026	0.027	0.027	0.027
Observations	309926	309926	309926	309926	309926	309926	309926	309926	309926	309926	309926	309926

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 emergence of agriculture and 0 otherwise. The panel spans from 22,000 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. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

4.4 Comparison with the Existing Extinction Studies

Existing studies, grounded in a macroevolutionary framework, document an inverse U-shaped relationship between megafauna extinction and the likelihood of pristine agriculture (Riahi, 2020; 2024). As detailed in Online Appendix C, this pattern has been established solely using cross-sectional variation at the macro-regional level, both conceptually and empirically. As a result, the relationship between extinction and the independent emergence of farming at the micro-regional level and over time remains unexplored.

As shown in the previous sections, both my theoretical framework and empirical analyses rely on micro-regional and time variation, revealing a *linear* relationship between extinction and the Neolithic transition. Furthermore, the proposed theory emphasizes *economic incentives* as the driving mechanism, rather than *evolutionary dynamics*. Taken together, the evidence suggests that at the micro-regional scale—and when accounting for temporal variation—extinction and the agricultural transition are linearly related, with economic incentives playing a central role.

This subsection provides additional evidence that lost biomass is a better predictor of the independent rise of farming when focusing on micro-regional and temporal variation. To demonstrate this, I conduct a series of “horse-race” regressions comparing my measure of lost biomass with the extinction rate and its squared term—variables used in Riahi’s studies—which measure the ratio of extinct large mammals. In particular, I use the $1^\circ \times 1^\circ$ grid-cell panel described in subsection 4.3, with the following specification:

$$\begin{aligned} \mathbb{1}_{i,t} = \alpha_0 &+ \alpha_1 \text{LostBiomass}_{i,t-1} + \alpha_2 \text{ExRate}_{i,t-1} + \alpha_3 \text{ExRate}_{i,t-1}^2 \\ &+ \text{PaleoFactors}_{i,t-1} \beta' + \text{Cell}_i \gamma' + \text{Time}_t \delta' + \epsilon_{i,t}, \end{aligned} \quad (29)$$

where $\text{ExRate}_{i,t-1}$ denotes the extinction rate of megafauna in cell i at $t-1$.³² The economic-incentive mechanism proposed in this study predicts $\alpha_1 > 0$, whereas the macroevolutionary mechanism advanced by Riahi (2020; 2024) predicts $\alpha_2 > 0$ and $\alpha_3 < 0$.

Table 6 shows that lost biomass is consistently positive and significant, while extinction rate and its square do not exhibit the expected inverted-U pattern. In the horse-race specification, the lost biomass coefficient triples in magnitude and remains robust to extensive

³²This variable corresponds to the one used by Riahi (2020; 2024). However, as his studies are based on cross-country analyses, they do not provide either cross-sectional measures of extinction rates at finer spatial scales or panel data on extinction rates. I therefore construct extinction rates using data from the *PHYLACINE* database. The correlation between my constructed country-level extinction rate and the measure used in Riahi’s studies is high (0.85). The difference stems from data sources: whereas Riahi uses extinction rates created by Sandom et al. (2014), I construct the measure using *PHYLACINE*. Notably, *PHYLACINE* (Faurby et al., 2020) is a more advanced resource and currently the most comprehensive and up-to-date database on prehistoric mammals.

Table 6: Horse-race regression: lost biomass vs. extinction rate in explaining independent transitions (grid-cell panel)

	Neolithic Revolution indicator						
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS
Lost biomass (t-1)	0.015*** (0.004)		0.045*** (0.006)	0.045*** (0.006)	0.045*** (0.006)	0.044*** (0.006)	0.044*** (0.006)
Extinction rate (t-1)		-0.029*** (0.005)	-0.084*** (0.008)	-0.080*** (0.008)	-0.081*** (0.008)	-0.080*** (0.008)	-0.080*** (0.008)
Extinction rate sqr. (t-1)		0.007* (0.004)	0.027*** (0.004)	0.026*** (0.004)	0.026*** (0.004)	0.026*** (0.004)	0.026*** (0.004)
Paleo-temperature (mean) (t-1)				-0.254*** (0.016)	-0.244*** (0.016)	-0.251*** (0.017)	-0.249*** (0.017)
Paleo-precipitation (mean) (t-1)				0.043* (0.023)	0.035 (0.023)	0.020 (0.022)	0.020 (0.022)
Paleo-temperature (std.) (t-1)					0.024*** (0.004)	0.026*** (0.004)	0.026*** (0.004)
Paleo-precipitation (std.) (t-1)					0.027** (0.012)	0.029** (0.012)	0.029** (0.012)
Paleo-net primary productivity (mean) (t-1)						0.029* (0.017)	0.030* (0.017)
Paleo-net primary productivity (std.) (t-1)						0.011 (0.007)	0.014* (0.008)
Paleo-ecological diversity (t-1)							-0.008* (0.005)
Outcome mean	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Cell FE	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓
Adjusted R-Sqr.	0.030	0.030	0.031	0.032	0.032	0.032	0.032
Observations	288340	288340	288340	288340	288340	288340	288340

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 emergence of agriculture and 0 otherwise. The panel spans from 22,000 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. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

paleo-climatic and environmental controls.³³

This analysis primarily exploits time variation within grid cells, but the same pattern emerges when relying solely on cross-sectional micro-regional variation.³⁴ Table F15 reports the results. Columns 1–3 include continent fixed effects, enabling within-continent compar-

³³I also test whether lost biomass exhibits a hump-shaped relationship, but find no evidence of such a pattern.

³⁴ $1^\circ \times 1^\circ$ grid cells are constructed using data on the independent emergence of farming from Larson et

isons, while Columns 4–7 include $10^\circ \times 10^\circ$ grid-cell block fixed effects, allowing for more localized comparisons. Across all specifications, lost biomass is positively and significantly associated with independent agricultural transitions, whereas extinction rate and its square consistently fail to exhibit an inverted-U pattern.³⁵

Tables F16 and F17 present the results of robustness checks using the 2SLS approach, in which lost biomass is instrumented by its IV, as described in subsection 3.4. The 2SLS estimates reaffirm that lost biomass is a strong and consistent predictor of the likelihood of pristine agriculture. In contrast, extinction rate and its squared term display inconsistent signs across specifications.

It should be noted that these results do not contradict or diminish the contributions of Riahi (2020; 2024). Because the analyses in this subsection focus on micro-regional and temporal dimensions that fall outside the intended scope of his theoretical framework and empirical approach, the results of these analyses are consistent with the conceptual differences between our theories. Taken together, my findings suggest that mammal extinction may have influenced the likelihood of the independent emergence of agriculture in different ways depending on the spatial scale and temporal dimension of analysis. Consequently, I view our studies as complementary rather than competitive.

4.5 Heterogeneity in Land Suitability for Agriculture

This subsection investigates the mechanism and generalizability of the findings so far, providing new insights into the long-standing puzzle of the origins of the Neolithic Revolution. Specifically, I examine (i) whether economic incentives drive the results, (ii) why pristine agriculture emerged in only a few regions of the world, and (iii) the role of agricultural productivity—an aspect often downplayed in the existing literature. To address these questions, I use the $1^\circ \times 1^\circ$ grid-cell panel data described in subsection 4.3 and analyze the heterogeneous effects of lost biomass with respect to land suitability for agriculture. The association

al. (2014). The association is estimated as:

$$\begin{aligned} \mathbb{1}_i = \alpha_0 &+ \alpha_1 \text{LostBiomass}_i + \alpha_2 \text{ExRate}_i + \alpha_2 \text{ExRate}_i^2 \\ &+ \text{PaleoFactors}_i \beta' + \text{Geo}_i \gamma' + FE_i \delta' + \epsilon_i, \end{aligned} \quad (30)$$

where $\mathbb{1}_i$ equals 1 if an independent emergence of agriculture occurred in cell i . ExRate_i is the extinction rate of megafauna in cell i , FE_i denotes either continent fixed effects or 10° grid-cell block fixed effects, and ϵ_i is the error term. Standard errors are adjusted for spatial correlation using the method of Conley (1999) with a 200 km cutoff.

³⁵Link (2024) also mentions that he does not find a hump-shaped relationship between extinction and the transition to farming when using granular grid-cell data.

is estimated using the following specification:

$$\begin{aligned} \mathbb{1}_{i,t} = & \alpha_0 + \alpha_1 \text{LostBiomass}_{i,t-1} + \alpha_2 \text{LostBiomass}_{i,t-1} \times \mathbb{1}_i^{\text{AgrSuitMed}} \\ & + \text{PaleoFactors}_{i,t-1} \beta' + \text{Cell}_i \gamma' + \text{Time}_t \delta' + \epsilon_{i,t}, \end{aligned} \quad (31)$$

where $\mathbb{1}_{i,t}$ takes 1 if grid cell i undergoes the independent rise of farming in period t , and $\mathbb{1}_i^{\text{AgrSuitMed}}$ takes 1 if grid cell i 's value of land suitability for agriculture is larger than the median.³⁶ The measure of land suitability is obtained from Ramankutty et al. (2002), a standard dataset in the literature (e.g., Michalopoulos, 2012; Henderson et al., 2018). Based on exogenous environmental conditions, this index measures the probability that land can be cultivated, capturing the degree to which land is biophysically suitable for agriculture.

Table 7 shows that the interaction term between lost biomass and land suitability dummy is positive and statistically highly significant. This indicates that the positive effect of lost biomass on independent agricultural transition is more pronounced in grid cells with greater land suitability for agriculture. In particular, Column 5 reveals that for grid cells above the median in land suitability, the total effect of lost biomass is 0.25 (= -0.07 + 0.257). This implies that, compared to grid cells with below-median suitability, a 1 percentage point increase in lost biomass increases the likelihood of transition by approximately 0.01 percentage point. Given that the mean and standard deviation of the dependent variable are 0.002 and 0.044, respectively, this effect is economically meaningful. Furthermore, this main result is robust to a 2SLS approach, as shown in Table F18.³⁷ Both the coefficient on lost biomass and its interaction with the land suitability dummy are positive and statistically highly significant.

The observed heterogeneity with respect to land suitability for agriculture offers several key insights. First, it further reinforces the role of economic incentives as a driving mechanism behind the Neolithic transition. Grid cells with higher agricultural suitability offered greater potential economic returns from farming. Thus, when these areas experienced significant loss of hunting resources due to megaherbivore extinction, the incentive to shift toward cultivation became stronger. While this heterogeneous effect is easily explained by economic incentives, macroevolutionary theory does not offer a straightforward explanation.

Second, this result helps explain why farming originated in only a limited number of regions worldwide.³⁸ As shown in Figure 3, only a small number of regions independently

³⁶Since grid cell fixed effects are included, a single term $\mathbb{1}_i^{\text{AgrSuitMed}}$ is dropped.

³⁷I instrument $\text{LostBiomass}_{i,t-1}$ and $\text{LostBiomass}_{i,t-1} \times \mathbb{1}_i^{\text{AgrSuitMed}}$ using $\widehat{\text{LostBiomass}}_{i,t-1}$ and $\widehat{\text{LostBiomass}}_{i,t-1} \times \mathbb{1}_i^{\text{AgrSuitMed}}$, where $\widehat{\text{LostBiomass}}_{i,t-1}$ is derived from equation (26).

³⁸Dow and Reed (2023) emphasize that a compelling theory of the Neolithic transition must account for why agriculture originated in only a limited number of regions worldwide. Most existing studies do not

Table 7: Heterogeneity with respect to agricultural suitability (independent transition)

	Neolithic Revolution indicator				
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS
Lost biomass (t-1)	-0.035** (0.014)	-0.011 (0.014)	-0.013 (0.014)	-0.007 (0.014)	-0.007 (0.014)
Lost biomass (t-1) \times land suitability dummy	0.283*** (0.057)	0.268*** (0.057)	0.269*** (0.057)	0.257*** (0.058)	0.257*** (0.058)
Paleo-temperature (mean) (t-1)		-0.254*** (0.015)	-0.245*** (0.015)	-0.252*** (0.016)	-0.250*** (0.016)
Paleo-precipitation (mean) (t-1)		0.057*** (0.022)	0.050** (0.022)	0.031 (0.021)	0.032 (0.021)
Paleo-temperature (std.) (t-1)			0.021*** (0.004)	0.024*** (0.004)	0.024*** (0.004)
Paleo-precipitation (std.) (t-1)			0.024** (0.011)	0.028** (0.012)	0.027** (0.012)
Paleo-net primary productivity (mean) (t-1)				0.035** (0.017)	0.035** (0.017)
Paleo-net primary productivity (std.) (t-1)				0.011 (0.007)	0.014* (0.008)
Paleo-ecological diversity (t-1)					-0.008* (0.004)
Outcome mean	0.002	0.002	0.002	0.002	0.002
Cell FE	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓
Adjusted R-Sqr.	0.026	0.027	0.027	0.027	0.027
Observations	306630	306630	306630	306630	306630

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 emergence of agriculture and 0 otherwise. The land suitability dummy equals 1 if a grid cell's land suitability for agriculture exceeds the median value, and 0 otherwise. The panel spans from 22,000 BP until the transition occurs, using 1,000-year time windows. All variables except for lost biomass (t-1) and its interaction with land suitability dummy are standardized. Robust standard errors, clustered at the grid cell level, are reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

developed domestication, and some regions experienced substantial megaherbivore extinction without independently initiating farming. The positive interaction between lost biomass and land suitability for agriculture provides a plausible explanation for this pattern: regions that

address this point.

experienced both substantial extinction and high suitability for agriculture were relatively rare. This suggests that both conditions were jointly necessary for the emergence of farming.

Lastly, this result speaks to a well-known puzzle of the Neolithic Revolution raised by Diamond (1997; 2002). He famously argues that agricultural productivity alone does not explain the emergence of farming—challenging the intuitive notion that agriculture should have developed wherever land was suitable. The finding that the effect of land suitability depends on the extent of lost hunting resources due to megaherbivore extinction provides a reasonable explanation to this puzzle. It suggests that agricultural productivity did matter, but only in contexts where the decline in foraging returns—driven by extinction—created economic incentives to adopt farming.

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, therefore, one of the most important questions in prehistory and is key to understanding the world today.

This study examines how human-driven extinction of megaherbivores influenced the Neolithic Revolution, using both theoretical and empirical approaches. It quantifies the reduction in hunting opportunities resulting from extinction events, utilizing newly compiled mammal-species datasets. Additionally, the study introduces an instrumental variable for mammal extinction, based on biological traits that increased vulnerability to hunting. Both the main variable and instrument are constructed for use in cross-sectional and panel analyses at various spatial scales, covering the entire world. These measures allow researchers to quantify mammal extinction globally and locally, in both cross-sectional and panel frameworks, depending on their analytical needs.

By combining complementary datasets and controlling for paleo-climatic and environmental factors—the most important confounders in this context—this study provides strong evidence that human-driven extinction of megaherbivores significantly influenced both the emergence and diffusion of agriculture. The findings are robust to the 2SLS approach, which instruments lost biomass using a measure of extinction risk based on biological traits associated with vulnerability to hunting pressure. The analysis reveals a *linear* relationship between extinction and the Neolithic Revolution, exploiting micro-regional and temporal variation. This contrasts with existing studies that rely on macro-regional, cross-sectional data and find a hump-shaped relationship. Moreover, the heterogeneity analysis based on land suitability for agriculture supports the proposed economic-incentive mechanism and of-

fers a plausible explanation for why only a limited number of regions independently adopted farming. This heterogeneity further demonstrates that agricultural productivity played a significant role in the rise of agriculture—a factor largely overlooked in the existing literature.

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

Appendix A

In this section, I summarize the historical records of large-herbivore extinction and the independent emergence 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).³⁹ 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

³⁹Based 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.

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 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.

40

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), 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

⁴⁰Piperno (2011) gives a similar argument based on the region from the Central Balsas of southwest Mexico to Bolivia.

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 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

Incorporating Gathering into the Model

In this subsection, I introduce gathering as an alternative production mode to the basic framework. The production function for gathering is given by:

$$Y_t^g = B^g (L_t^g)^{1-\beta} \quad (32)$$

where B^g represents the biomass of edible plants. For simplicity and tractability, I assume B^g remains constant.

The population consists of females and males, with their respective fractions given by q

and $1 - q$.⁴¹ In a typical foraging society, females engage in gathering, while males engage in hunting. Thus, the total labor allocation is given by:

$$L_t = L_t^h + L_t^g = (1 - q)L_t + qL_t. \quad (33)$$

In foraging societies, individuals commonly share their hunted and gathered resources with the community. As a result, total output and per capita output from foraging are given by:

$$Y_t^f = (1 - q)^{1-\alpha} A^h B_t^\alpha L_t^{1-\alpha} + q^{1-\beta} B^g L_t^{1-\beta} \quad (34)$$

and

$$y_t^f = (1 - q)^{-\alpha} A^h B_t^\alpha L_t^{-\alpha} + q^{-\beta} B^g L_t^{-\beta}. \quad (35)$$

Then, the *Foraging-Farming Frontier* is defined as the geometric locus of (B_t, L_t) such that, given exclusive employment of the labor force in the foraging sector (that is, $L_t = L_t^h + L_t^g$), a member of generation t is indifferent between supplying their labor to the foraging sector and supplying it to the agricultural sector (that is, $y_t^f = y_t^a$). In particular, assuming $\alpha = \beta$, it is given by

$$yy^{FF} \equiv \left\{ (B_t, L_t) : L_t = \left[\frac{\{(1 - q)^{-\alpha} A^h B_t^\alpha + q^{-\alpha} B^g\}}{A_t^a} \right]^{\frac{1}{\alpha}} \right\}. \quad (36)$$

Let (B_t^f, L_t^f) represent the biomass and population size along the Foraging-Farming Frontier. By comparing equations (35) and (4), we obtain the condition:

$$y_t \gtrless y_t^a \Leftrightarrow L_t \gtrless L_t^f. \quad (37)$$

Furthermore, some calculations yield:

$$\frac{\partial L_t^f}{\partial B_t^f} > 0 \quad \text{and} \quad \frac{\partial^2 L_t^f}{\partial B_t^2} < 0. \quad (38)$$

Thus, the Foraging-Farming Frontier is a strictly increasing and concave function of B_t . Moreover, it is easy to show: $\partial L_t^f / \partial A_t^a < 0$.

As with the basic model, we can examine the impact of extinction and biological vul-

⁴¹These fractions remain constant over time, and naturally, $q \approx 0.5$.

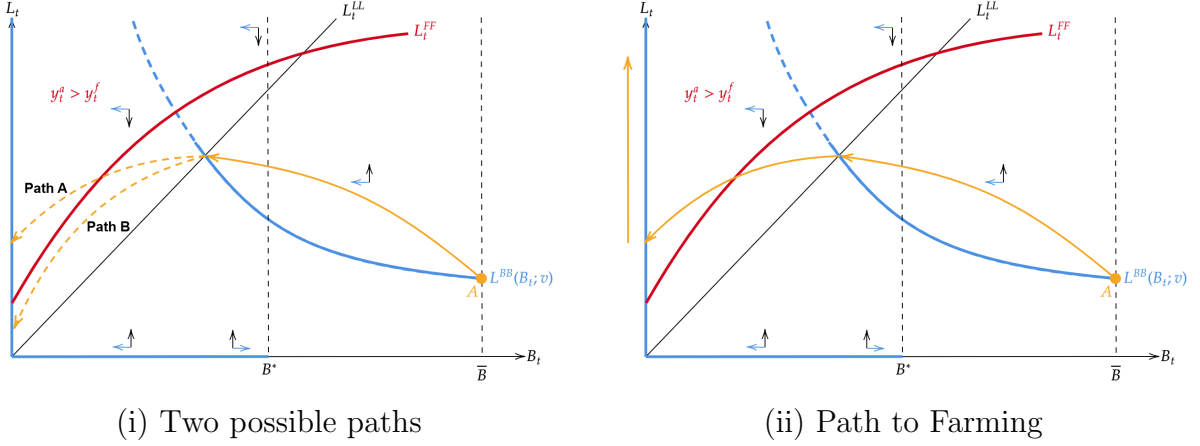


Figure 6: Transition to Farming

nerability on the transition to farming. However, even if the economy crosses the biological threshold $B^*(v)$ due to high biological vulnerability, the transition is not guaranteed. Panel (i) of Figure 6 illustrates two possible paths the economy may follow after surpassing $B^*(v)$. If it follows Path A, the cultivation of wild plants begins, leading to the transition to farming. In contrast, if it follows Path B, the transition never occurs. This outcome depends on factors such as gathering output B^g and the rate of decline of population. If population decline is minimal and gathering output is not substantial, or a combination of these factors occurs, the economy is more likely to follow Path A. Panel (ii) of Figure 6 illustrates a scenario where at least one of these conditions holds, enabling the economy to transition to farming through the learning-by-doing effect.

Solution to the Neolithic Puzzle

The Neolithic Revolution presents a puzzle: Why did early farmers adopt agriculture despite its initial failure to increase consumption and its demand for longer working hours? The following proposition offers a solution.

Proposition 2 *Suppose that $y_t^a < y_t^h$ and $y_d^a = y_d^h$ for $t \in [0, d-1]$, and that $\exists f \geq d+1$ s.t. $n[y_{f-1}^a] < 1 \leq n[y_f^a]$. Then, $\exists t^* \geq d+1$ s.t. for $i \in [d, t^*-1]$ and $m \in [0, d-1]$,*

i. $y_i^a < y_m^h$; and

ii. $w_i^a > w_m^h$.

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 $\forall j \in [c+1, d-1]$, $y_i^a < y_j^h$. For $j \in [c+1, d-1]$, the economy is below the Hunting-Farming Frontier, L^{yy} . Thus, $L_j^h < (A^h/A_j^a X^a)B_j$. Since $y_d^a = y_d^h$, 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: $A_0^a = A_a^a = \dots = A_d^a < A_{d+1}^a < \dots$. Therefore, there exists $t^* \geq d+1$ s.t. for $j \in [c+1, d-1]$, $L_j^h < (A^h/A_{t^*-1}^a X^a)^{1/\alpha} B_j$ and $L_j^h \geq (A^h/A_{t^*}^a X^a)^{1/\alpha} B_j$. From (2) and (4), $y_i^a < y_j^h$.

Then, I show that for this t^* , $y_i^a < y_k^h \forall i \in [d, t^* - 1]$ 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_j^{LL} . Thus, $n[y_j^h] < 1 \leq n[y_k^h]$. From (11) and (12), $y_j^h < y_k^h$. Since $y_i^a < y_j^a$, we have $y_i^a < y_k^h$ for $i \in [d, t^* - 1]$.

Therefore, I showed: $\exists t^* \geq d+1$ s.t. $\forall i \in [d, t^* - 1]$ and $\forall m \in [0, d-1]$, $y_i^a < y_m^h$. As shown in (11), $\partial w_t^*/\partial y_t < 0$. Thus, $w_i^a > w_m^h$. ■

Appendix C

In this appendix, I clarify the key differences between my research and the studies by Riahi (2020; 2024). Although we both examine the relationship between mammal extinction and the independent rise of farming, there are substantial differences in our conceptual frameworks, empirical methodologies, and findings.⁴²

Difference in Conceptual Framework

Although Riahi does not present a formal model, he provides a plausible explanation that megafauna extinction triggered the evolution of domestication at the macro-regional scale, proposing a macroevolutionary mechanism involving interactions among humans, animals, plants, ecology, institutions, and culture.

The theory starts with this premise: In Africa, long coevolution allowed animals to evolve strategies to evade human hunters, making extinction rare. In contrast, humans arrived recently in the Americas, where animals lacked such defenses, leading to extensive extinctions. In Eurasia, hominin migration was gradual, resulting in moderate extinction levels.

During the Pleistocene, plants coevolved with large mammals, relying on them for seed dispersal and evolving defenses against herbivory. After megafauna extinction, plants adapted by depending more on humans and reducing costly defenses, increasing their accessibility.

⁴²Subsection 4.4 outlines differences in the findings, which align with the conceptual and methodological distinctions discussed in this appendix.

Extinction of large mammals incentivized herd management and domestication, encouraging cultures and institutions that supported cooperation and sedentism—precursors to farming. It also fostered collective hunting and trust-building. Manageable, regenerating resources promoted self-organization, often forming polycentric systems that facilitated sedentary life and agriculture.

The theory thus offers three comparative conclusions: (i) In Africa, predator-savvy mammals reduced extinction risk and the need for intertribal cooperation. Limited domesticability and stable ecosystems kept plants independent from humans, sustaining hunting and tribal structures and discouraging farming. (ii) In the Americas, naïve fauna faced high extinction pressure, encouraging cooperation. However, weak evolutionary ties hindered human control over animal life cycles, and plants dependent on megafauna adapted poorly to human use, delaying sedentism and farming. (iii) In Eurasia, moderately predator-savvy animals and steady ecological pressures promoted trust and organized hunting. Plants and animals adapted more readily to human use, supporting cooperation, sedentism, domestication, and farming.

To sum up, the theory predicts a hump-shaped relationship between megafauna extinction and the independent emergence of agriculture, with macroevolution as the underlying mechanism. It focuses on macro-regional variation—such as differences across continents or regions in exposure to hominin species including *Homo erectus*, *Homo neanderthalensis*, Denisovans, and *Homo sapiens*—to explain patterns of extinction and the origins of agriculture. As a result, it provides limited insight into how micro-regional and temporal variation account for the relationship between extinction and the rise of farming.^{43,44} Moreover, the theory aims to explain the independent emergence of agriculture, not its diffusion.

In contrast, as detailed in the main text, my theory emphasizes *economic incentives* as a key mechanism of the Neolithic Revolution, providing a unified explanation for both the *independent emergence* and the subsequent *diffusion* of farming. It applies straightforwardly to macro-regional, *micro-regional*, and *temporal* variation. Finally, my economic incentive theory predicts a *positive linear* relationship.

⁴³Riahi explicitly acknowledges this point: “Therefore, this study has no explanatory power for the emergence of agriculture (or lack thereof) in regions that were occupied by hominins around the same time” (Riahi, 2020, p.228), and “The theory has limited explanatory power for within-region variation in the outcomes” (Riahi, 2024, p.18).

⁴⁴According to the theory, once megafauna extinction occurs in a large region, time variation within that region alone does not explain the emergence of agriculture. Instead, it is the cross-sectional differences across macro-regions after extinction that matter.

Difference in Empirical Methodologies

Riahi (2020; 2024) empirically also relies exclusively on macro-regional variation and leverages cross-country data. It is important to note that his focus on cross-country variation is appropriate for testing his hypothesis, as the theory conceptualizes the link between megafauna extinction and pristine agriculture at the macro-regional scale, relying on cross-sectional rather than micro-regional or time variation.

While I acknowledge the validity of his focus on cross-country data for his study, there are important methodological differences between our approaches, as they lead to distinct levels of causal inference and identification. First, I leverage finer spatial resolution, using $1^\circ \times 1^\circ$ grid cells, and incorporates time variation through panel data. Second, while he treats mammalian extinction as exogenous, I consider it endogenous and address this concern through panel regressions and an IV approach.

Modern countries serve as a noisy proxy for studying the Neolithic Revolution. During the period of agricultural emergence, contemporary national borders did not exist. All instances of independent domestication occurred long before the formation of modern states, and the same holds true for the global diffusion of farming, with only a few exceptions. To address this limitation, I use data on prehistoric human settlements and conduct fine-grained, grid-cell-level analyses.

Cross-country analysis also suffers from endogeneity, as the endogenous formation of present-day national borders may obscure the true relationship between extinction and the Neolithic transition. Moreover, the cross-sectional nature precludes controlling for time-invariant country characteristics, country-invariant temporal variation, and time-varying country-specific confounders (e.g., time-varying paleo-climate and environmental factors). My grid-cell-level panel data approach addresses these concerns by allowing for control over major sources of bias.⁴⁵

Riahi treats extinction as exogenous.⁴⁶ However, this assumption is questionable due to (i) potential reverse causality and (ii) unobserved confounding factors such as local institutions, culture, or geography. Riahi’s measures of extinction include species that went extinct

⁴⁵As discussed in the main text, paleo-climatic conditions are a primary source of confounding in this context. These time-varying, unit-specific factors are most effectively addressed within a panel data framework.

⁴⁶*“In Africa, the birthplace of Homo, extinction was a rare event. Meanwhile, Homo sapiens’ occupation of the New World, where fauna and flora evolved in isolation, resulted in mass extinction events. Hominins gradually occupied Eurasia over the past two million years, and the LQE was comparatively moderate on this continent. Empirical analyses of the paper exploit these exogenous differences to explain the emergence and prevalence of agriculture.”* (Riahi, 2020) and *“The paper’s empirical analyses exploit the variation in extinction rates as a source of exogenous pressure on humans to change their interactions with nature (constructed niches) and each other (societal institutions) and examine the impact of extinction on long-run development.”* (Riahi, 2024).

by 1000 BP.⁴⁷ This is problematic because all independent transitions to agriculture and much of its subsequent spread occurred long before these periods.

In my study, I exclude species that went extinct after agricultural transitions in cross-sectional analyses and use one-period lagged extinction in panel analyses to mitigate concerns about reverse causality. To address potential unobserved confounding factors, the panel analyses incorporate time-varying paleo-climatic features, grid-cell fixed effects, and time fixed effects. Additionally, I employ the IV approach to show further robustness.

Lastly, our studies also differ in their key variables of interest. While Riahi uses the ratio of extinct megafauna species, I construct a measure of lost biomass that incorporates species' distribution, variety, abundance, and body mass, offering a more comprehensive indicator of hunting-resource loss.

Appendix D

Outcome Variables

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 of Neolithic settlement. This data is taken from Pinhasi et al. (2005) and Cobo et al. (2019). For the analysis of independent transitions, it refers to the earliest date of the first domestication for regions of well-accepted agricultural centers (Larson et al., 2014).

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 Andermann et al. (2020).

Independent Variables

Lost biomass: 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

⁴⁷Although he does not explicitly mention this, Sandom et al. (2014), the sources for these measures, clarify their inclusion of these species.

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.

Extinction rate: This variable represents the ratio of extinct large mammal species to the total number of mammal species, including herbivores, carnivores, and omnivores. For the grid-cell analyses, the variable is constructed by the author, using the *PHYLACINE* and Andermann et al. (2020).

Control Variables

Paleo-temperature, paleo-precipitation, and paleo-net primary productivity (mean and standard deviation): The average and standard deviation of temperature, precipitation, and net primary productivity 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-ecological diversity: Ecological diversity for a given area is calculated using data from Beyer et al. (2020). For a particular unit, it is defined as:

$$1 - \sum_{j \in J} \frac{AreaBiome_j}{TotalArea}$$

where j represents a biome type, J is the set of all biomes, $AreaBiome_j$ is the area occupied by biome j , and $TotalArea$ is the total land area of the unit of interest.

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.

Distance to the nearest agricultural center: For countries, this is the geodesic distance to the nearest center of agricultural origin, constructed following the methodology of Ashraf and Michalopoulos (2015).

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*.

Land Suitability for Agriculture: A measure of overall land quality for agriculture, sourced from Ramankutty et al. (2002), who construct it as the product of climatic and soil suitability components. I calculate the average and standard deviation across grid cells within each spatial unit. I also construct the above-median dummy that equals 1 if the land suitability value exceeds the median across all cross-sectional observations.

Terrain ruggedness: The variable is created as a weighted average of ruggedness with a surface area being a weight, following the data construction by Nunn and Puga (2012).

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

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.

Appendix E

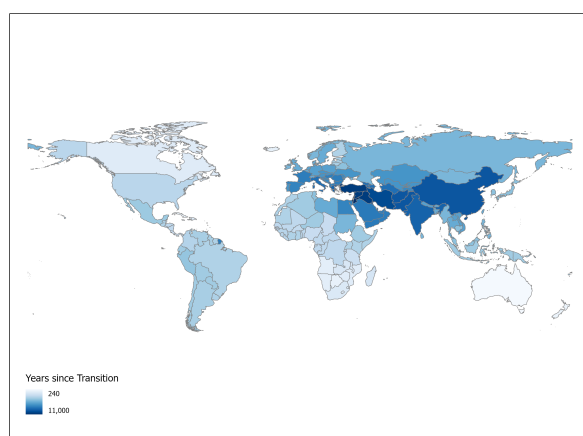


Figure E1: Years elapsed since the Neolithic Revolution (Borcan et al., 2018)

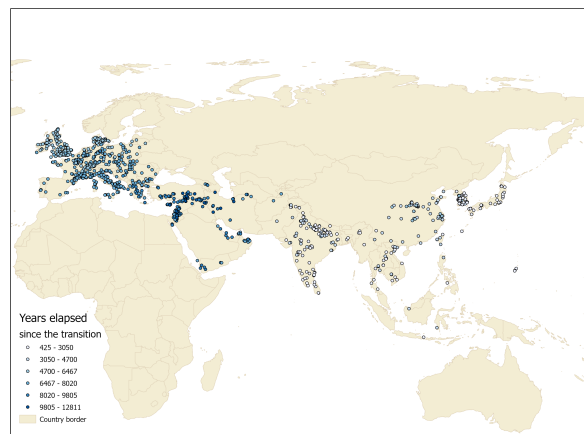


Figure E2: Years elapsed since the Neolithic Revolution (Pinhasi et al., 2005; Cobo et al., 2019)

Appendix F

Table F1: Summary statistics (cross-country)

	Mean	SD	Min	Max	N
<i>Dependent variable</i>					
Years elapsed since the Neolithic Revolution (in 100 Years)	46.83	24.64	2.44	105.00	171
<i>Independent variables</i>					
Lost biomass	0.50	0.41	0.00	1.00	164
<i>Control variables</i>					
Paleo-temperature (mean)	13.43	10.90	-28.12	24.82	181
Paleo-precipitation (mean)	1,054.87	714.36	39.83	3,042.57	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 (mean)	483.06	363.47	0.00	1476.94	181
Paleo-net primary productivity (std.)	119.76	99.00	0.00	443.44	181
Ecological diversity	0.45	0.24	0.00	0.90	181
Log dist. to the nearest agricultural origin	7.51	1.45	0.00	8.88	236
Absolute latitude	25.35	17.05	1.00	72.00	200
Land suitability for agriculture (mean)	0.40	0.26	0.00	0.96	171
Land suitability for agriculture (std.)	0.17	0.10	0.00	0.40	171
Terrain ruggedness	130052.46	125672.51	0.00	670995.75	234
Total area	573490.07	1746482.05	0.71	16973512.00	234
Log dist. to the nearest waterway	5.01	1.31	2.19	7.78	164

Table F2: Summary statistics (archaeological site panel)

	Mean	SD	Min	Max	N
<i>Dependent variable</i>					
Dummy the Neolithic transition	0.057	0.232	0.000	1.000	9047
<i>Independent variables</i>					
Lost biomass (t-1)	0.018	0.089	0.000	1.000	8920
Lost biomass (t+1)	0.023	0.098	0.000	1.000	8905
Lost biomass (Currie, 1993) (t-1)	0.018	0.084	0.000	1.000	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
Extinction rate (t-1)	0.00	0.01	0.00	0.13	7754
<i>Instrumental variable</i>					
Lost biomass (IV) (t-1)	0.04	0.00	0.03	0.04	8403
<i>Control variables</i>					
Paleo-temperature (mean) (t-1)	11.27	8.65	-20.27	28.13	8927
Paleo-precipitation (mean) (t-1)	942.74	512.01	50.27	3956.11	8927
Paleo-temperature (std.) (t-1)	0.65	0.71	0.00	4.80	8927
Paleo-precipitation (std.) (t-1)	76.38	79.45	0.00	731.14	8927
Paleo-net primary productivity (mean) (t-1)	391.02	260.93	0.00	1872.96	8927
Paleo-net primary productivity (std.) (t-1)	44.87	54.71	0.00	362.06	8927
Paleo-ecological diversity (t-1)	0.17	0.23	0.00	0.75	8600
Intermonthly temperature volatility. (t-1)	7.05	2.54	0.35	16.92	7937
Temperature (seasonality) (t-1)	13.38	6.47	0.00	31.18	5790
Precipitation (seasonality) (t-1)	1.31	0.71	0.13	3.40	5790

Table F3: Summary statistics (independent transition cell panel)

	Mean	SD	Min	Max	N
<i>Dependent variable</i>					
Dummy the Neolithic transition	0.002	0.042	0.000	1.000	426880
<i>Independent variables</i>					
Lost biomass (t-1)	0.035	0.138	0.000	1.000	360160
Lost biomass (t+1)	0.036	0.142	0.000	1.000	342798
Lost biomass (Currie, 1993) (t-1)	0.035	0.134	0.000	1.000	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
Extinction rate (t-1)	0.01	0.03	0.00	1.00	352708
<i>Instrumental variable</i>					
Lost biomass (IV) (t-1)	0.04	0.00	0.03	0.04	356575
<i>Control variables</i>					
Paleo-temperature (mean) (t-1)	3.44	17.84	-47.13	30.15	408427
Paleo-precipitation (mean) (t-1)	655.39	690.08	0.00	7285.33	408427
Paleo-temperature (std.) (t-1)	0.53	0.64	0.00	9.43	408427
Paleo-precipitation (std.) (t-1)	43.43	82.84	0.00	2121.54	408427
Paleo-net primary productivity (mean) (t-1)	340.97	374.54	0.00	2271.00	408427
Paleo-net primary productivity (std.) (t-1)	32.08	51.17	0.00	910.00	408427
Paleo-ecological diversity (t-1)	0.13	0.21	0.00	0.81	362538
Intermonthly temperature volatility. (t-1)	9.87	6.37	0.25	30.33	378241
Temperature (seasonality) (t-1)	8.60	7.69	0.00	33.36	304006
Precipitation (seasonality) (t-1)	1.35	0.71	0.05	3.88	304006

Table F4: Hunting dependency and lost biomass

	Hunting dependency				
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS
Lost biomass	-0.39*** (0.09)	-0.33*** (0.05)	-0.40*** (0.05)	-0.37*** (0.05)	-0.28*** (0.06)
Paleo-temperature (mean)		-0.38*** (0.05)	-0.16*** (0.05)	-0.21*** (0.05)	-0.20*** (0.07)
Paleo-precipitation (mean)		-0.03 (0.04)	0.17*** (0.04)	0.03 (0.07)	0.00 (0.05)
Paleo-temperature (std.)			0.31*** (0.09)	0.27*** (0.08)	0.24** (0.09)
Paleo-precipitation (std.)			-0.14** (0.05)	-0.08 (0.06)	-0.03 (0.04)
Paleo-net primary productivity (mean)				0.15** (0.06)	0.14** (0.06)
Paleo-net primary productivity (std.)				-0.09*** (0.03)	-0.07** (0.03)
Paleo-ecological diversity				-0.02 (0.03)	-0.02 (0.03)
Outcome mean	1.51	1.51	1.51	1.51	1.51
Continent FE	✓	✓	✓	✓	✓
Geographical controls					✓
Adjusted R^2	0.39	0.47	0.49	0.50	0.51
Observations	1131	1131	1131	1131	1131

Note: The unit of analysis is the ethnic group, as defined in the *Ethnographic Atlas*. Continent fixed effects include Africa, the Americas, Asia, Europe, and Oceania. Geographic controls are log distance to the nearest agricultural origin, absolute latitude, mean and standard deviation of land suitability for agriculture, terrain ruggedness, land area, and log distance to the nearest waterway. All variables are standardized. Robust standard errors are clustered at the language group level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table F5: Extinction and digestive inefficiency

	(1)	(2)	(3)	(4)	(5)	(6)
	Logit	Logit	Logit	Logit	Logit	Logit
Dummy extinction						
Fermentation inefficiency	1.13*** (0.21)		1.06*** (0.23)	1.10*** (0.23)	1.04*** (0.23)	1.03*** (0.26)
Body mass		0.95** (0.39)	0.22 (0.27)	0.20 (0.28)	0.24 (0.28)	0.26 (0.26)
Paleo-temperature (mean)				-0.24 (0.19)	-0.43* (0.26)	0.09 (0.33)
Paleo-precipitation (mean)				0.05 (0.18)	0.24 (0.25)	-0.21 (0.65)
Paleo-temperature (std.)					-0.24 (0.24)	-0.17 (0.28)
Paleo-precipitation (std.)					-0.25 (0.33)	-0.08 (0.26)
Paleo-net primary productivity (mean)						0.64 (0.78)
Paleo-net primary productivity (std.)						-0.67** (0.33)
Paleo-ecological diversity						1.05*** (0.28)
Outcome mean	0.50	0.50	0.50	0.50	0.50	0.50
Pseudo- R^2	0.18	0.06	0.19	0.19	0.20	0.26
Observations	181	181	181	181	181	181

Note: The unit of analysis is species classified as megaherbivores. The dependent variable is a binary indicator equal to 1 if a species went extinct and 0 otherwise. All variables except for the dependent variable are standardized. Robust standard errors are reported. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table F6: Robustness to alternative measures of lost biomass (archaeological site panel)

	Neolithic Revolution indicator				
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS
Lost biomass (Currie, 1993)	0.094*** (0.020)				
Lost biomass (Damuth, 1987)		0.098*** (0.020)			
Lost biomass (Peters and Raelson, 1984)			0.101*** (0.021)		
Lost biomass (Peters and Wassenberg, 1983)				0.094*** (0.020)	
Lost biomass (Silva et al., 2001)					0.096*** (0.020)
Outcome mean	0.063	0.063	0.063	0.063	0.063
Cell FE	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓
Paleo-climatic controls	✓	✓	✓	✓	✓
Adjusted R-Sqr.	0.318	0.318	0.318	0.318	0.318
Observations	7504	7504	7504	7504	7504

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 22,000 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, paleo-precipitation, and paleo-net primary productivity, and paleo-ecological diversity. 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 F7: Robustness to lost biomass including 14 domesticable mammals (archaeological site panel)

	Neolithic Revolution indicator				
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS
Lost biomass (t-1)	0.087*** (0.017)	0.086*** (0.016)	0.087*** (0.016)	0.082*** (0.017)	0.083*** (0.017)
Paleo-temperature (mean) (t-1)		0.347*** (0.082)	0.448*** (0.088)	0.673*** (0.090)	0.674*** (0.090)
Paleo-precipitation (mean) (t-1)		-0.557*** (0.062)	-0.593*** (0.065)	-0.349*** (0.072)	-0.349*** (0.072)
Paleo-temperature (std.) (t-1)			0.181** (0.078)	0.094 (0.078)	0.093 (0.078)
Paleo-precipitation (std.) (t-1)			0.131*** (0.050)	0.093* (0.051)	0.094* (0.050)
Paleo-net primary productivity (mean) (t-1)				-0.482*** (0.070)	-0.482*** (0.070)
Paleo-net primary productivity (std.) (t-1)				-0.070** (0.027)	-0.067** (0.028)
Paleo-ecological diversity (t-1)					-0.009 (0.021)
Outcome mean	0.059	0.059	0.059	0.059	0.059
Cell FE	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓
Adjusted R-Sqr.	0.297	0.311	0.313	0.320	0.320
Observations	7988	7988	7988	7988	7988

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 22,000 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 F8: Robustness to intermonthly temperature volatility and climatic seasonality (archaeological site panel)

	Neolithic Revolution indicator									
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS	(9) OLS	(10) OLS
Lost biomass (t-1)	0.097*** (0.019)	0.097*** (0.019)	0.097*** (0.019)	0.093*** (0.019)	0.093*** (0.019)	0.111*** (0.025)	0.116*** (0.025)	0.116*** (0.025)	0.114*** (0.025)	0.115*** (0.025)
Intermonthly temperature vol. (t-1)	-0.145 (0.448)	-0.209 (0.428)	-0.200 (0.426)	-0.194 (0.401)	-0.194 (0.401)					
Intermonthly temperature vol. sqr. (t-1)	1.130*** (0.385)	0.976** (0.387)	0.991** (0.387)	1.009*** (0.353)	1.009*** (0.354)					
Temperature (seasonality) (t-1)						1.612*** (0.120)	1.509*** (0.136)	1.489*** (0.137)	1.423*** (0.134)	1.422*** (0.135)
Precipitation (seasonality) (t-1)						-0.207* (0.115)	-0.142 (0.114)	-0.146 (0.114)	-0.182 (0.117)	-0.182 (0.117)
Paleo-temperature (mean) (t-1)		0.073 (0.107)	0.184 (0.114)	0.407*** (0.109)	0.407*** (0.109)		-0.096 (0.112)	0.027 (0.134)	0.347** (0.136)	0.347** (0.136)
Paleo-precipitation (mean) (t-1)		-0.574*** (0.063)	-0.610*** (0.065)	-0.355*** (0.074)	-0.355*** (0.074)		-0.292*** (0.070)	-0.321*** (0.074)	-0.041 (0.080)	-0.041 (0.080)
Paleo-temperature (std.) (t-1)			0.215*** (0.081)	0.124 (0.081)	0.124 (0.081)			0.168 (0.115)	0.070 (0.114)	0.070 (0.114)
Paleo-precipitation (std.) (t-1)			0.137*** (0.051)	0.102* (0.053)	0.102* (0.053)			0.102 (0.065)	0.067 (0.064)	0.068 (0.064)
Paleo-net primary productivity (mean) (t-1)				-0.490*** (0.072)	-0.490*** (0.072)				-0.512*** (0.084)	-0.512*** (0.084)
Paleo-net primary productivity (std.) (t-1)				-0.088*** (0.029)	-0.088*** (0.030)				-0.041 (0.029)	-0.040 (0.031)
Paleo-ecological diversity (t-1)					-0.000 (0.023)					-0.003 (0.027)
Outcome mean	0.063	0.063	0.063	0.063	0.063	0.069	0.069	0.069	0.069	0.069
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Adjusted R-Sqr.	0.303	0.314	0.315	0.322	0.322	0.332	0.333	0.334	0.339	0.339
Observations	7504	7504	7504	7504	7504	5596	5596	5596	5596	5596

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 22,000 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 F9: Restricted sample to Cobo et al. (2019) (archaeological site panel)

	Neolithic Revolution indicator				
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS
Lost biomass (t-1)	0.024*** (0.004)	0.021*** (0.005)	0.021*** (0.005)	0.021*** (0.005)	0.021*** (0.005)
Paleo-temperature (mean) (t-1)		0.160 (0.286)	0.157 (0.287)	0.044 (0.316)	0.086 (0.318)
Paleo-precipitation (mean) (t-1)		0.120 (0.087)	0.124 (0.085)	0.069 (0.094)	0.067 (0.094)
Paleo-temperature (std.) (t-1)			0.370** (0.173)	0.388** (0.177)	0.389** (0.179)
Paleo-precipitation (std.) (t-1)			0.040 (0.054)	0.059 (0.052)	0.058 (0.052)
Paleo-net primary productivity (mean) (t-1)				0.099 (0.089)	0.102 (0.089)
Paleo-net primary productivity (std.) (t-1)				-0.049 (0.042)	-0.060 (0.044)
Paleo-ecological diversity (t-1)					0.028 (0.032)
Outcome mean	0.051	0.051	0.051	0.051	0.051
Cell FE	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓
Adjusted R-Sqr.	0.519	0.519	0.520	0.520	0.520
Observations	3401	3401	3401	3401	3401

Note: The unit of analysis is a $1^\circ \times 1^\circ$ grid cell. The sample consists exclusively of archaeological sites reported by Cobo et al. (2019). The dependent variable is a dummy that equals 1 if a grid cell undergoes an agricultural transition and 0 otherwise. The panel spans from 22,000 BP until the transition occurs, using 1,000-year time windows. All variables except for the dependent variable 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 F10: Restricted sample to Pinhasi et al. (2005) (archaeological site panel)

	Neolithic Revolution indicator											
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS	(9) OLS	(10) OLS	(11) OLS	(12) OLS
Lost biomass (t-1)	0.007 (0.030)	0.001 (0.029)	0.001 (0.029)	0.008 (0.030)	0.045* (0.027)	0.037 (0.027)	0.038 (0.027)	0.038 (0.027)	0.132*** (0.026)	0.144*** (0.027)	0.145*** (0.027)	0.145*** (0.027)
Paleo-temperature (mean) (t-1)		-1.207*** (0.093)	-1.165*** (0.099)	-0.858*** (0.101)		-1.093*** (0.089)	-1.033*** (0.095)	-0.721*** (0.102)		-0.782*** (0.069)	-0.699*** (0.076)	-0.365*** (0.102)
Paleo-precipitation (mean) (t-1)		0.037 (0.080)	0.045 (0.099)	0.095 (0.105)		-0.033 (0.076)	-0.043 (0.093)	0.007 (0.098)		-0.168** (0.074)	-0.201** (0.088)	-0.158* (0.092)
Paleo-temperature (std.) (t-1)			0.097 (0.066)	-0.002 (0.070)			0.126* (0.064)	0.027 (0.068)			0.164*** (0.061)	0.076 (0.064)
Paleo-precipitation (std.) (t-1)			-0.044 (0.079)	-0.078 (0.081)			-0.022 (0.076)	-0.056 (0.077)			0.007 (0.071)	-0.017 (0.072)
Paleo-net primary productivity (mean) (t-1)				-0.487*** (0.088)				-0.494*** (0.083)				-0.483*** (0.074)
Paleo-net primary productivity (std.) (t-1)				0.083*** (0.031)				0.083*** (0.030)				0.067** (0.030)
Paleo-ecological diversity (t-1)				-0.020 (0.023)				-0.023 (0.023)				-0.049* (0.026)
Outcome mean	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓								
Time FE (2000 years)					✓	✓	✓	✓				
Time FE (3000 years)									✓	✓	✓	✓
Adjusted R-Sqr.	0.460	0.481	0.481	0.486	0.458	0.476	0.476	0.480	0.359	0.369	0.369	0.374
Observations	4587	4587	4587	4587	4587	4587	4587	4587	4587	4587	4587	4587

Note: The unit of analysis is a $1^\circ \times 1^\circ$ grid cell. The sample consists exclusively of archaeological sites reported by Pinhasi et al. (2005). The dependent variable is a dummy that equals 1 if a grid cell undergoes an agricultural transition and 0 otherwise. The panel spans from 22,000 BP until the transition occurs, using 1,000-year time windows. All variables except for the dependent variable 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 F11: Probit regression (archaeological site panel)

	Panel A: OLS The NR dummy				Panel B: 2SLS The NR dummy			
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) 2SLS	(6) 2SLS	(7) 2SLS	(8) 2SLS
=1 if the Neolithic Transition Occures, =0 Otherwise								
Lost biomass (t-1)	0.178*** (0.028)	0.145*** (0.033)	0.151*** (0.033)	0.134*** (0.033)	0.978*** (0.041)	0.565* (0.335)	0.592* (0.319)	0.632** (0.270)
Paleo-temperature (mean) (t-1)		-0.306*** (0.054)	-0.297*** (0.054)	-0.273*** (0.059)		-0.233** (0.099)	-0.216** (0.100)	-0.183** (0.092)
Paleo-precipitation (mean) (t-1)		-0.670*** (0.079)	-0.699*** (0.084)	-0.556*** (0.076)		-0.628*** (0.100)	-0.648*** (0.107)	-0.501*** (0.094)
Paleo-temperature (std.) (t-1)			0.084 (0.071)	0.070 (0.071)			0.093 (0.063)	0.083 (0.060)
Paleo-precipitation (std.) (t-1)			0.050 (0.041)	0.025 (0.043)			0.045 (0.038)	0.019 (0.040)
Paleo-net primary productivity (mean) (t-1)				-0.175*** (0.061)				-0.162*** (0.054)
Paleo-net primary productivity (std.) (t-1)				-0.082* (0.042)				-0.050 (0.047)
Paleo-ecological diversity (t-1)				0.085** (0.042)				0.055 (0.041)
Outcome mean	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
Time FE	✓	✓	✓	✓	✓	✓	✓	✓
Pseudo R-Sqr.	0.431	0.524	0.527	0.533				
Observations	7984	7984	7984	7984	7984	7984	7984	7984

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 22,000 BP until the transition occurs, using 1,000-year time windows. All variables except for the dependent variable 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 F12: Robustness to alternative measures of lost biomass (independent transition)

	Neolithic Revolution indicator				
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS
Lost biomass (Currie, 1993) (t-1)	0.023*** (0.006)				
Lost biomass (Damuth, 1987) (t-1)		0.023*** (0.006)			
Lost biomass (Peters and Raelson, 1984) (t-1)			0.021*** (0.006)		
Lost biomass (Peters and Wassenberg, 1983) (t-1)				0.023*** (0.006)	
Lost biomass (Silva et al., 2001) (t-1)					0.023*** (0.006)
Outcome mean	0.002	0.002	0.002	0.002	0.002
Cell FE	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓
Paleo-climatic controls	✓	✓	✓	✓	✓
Adjusted R-Sqr.	0.030	0.030	0.030	0.030	0.030
Observations	299027	299027	299027	299027	299027

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 emergence of agriculture and 0 otherwise. The panel spans from 22,000 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, paleo-precipitation, and paleo-net primary productivity, and paleo-ecological diversity. 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 F13: Robustness to lost biomass including 14 domesticable mammals (independent transition)

	Neolithic Revolution indicator				
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS
Lost biomass (t-1)	0.015*** (0.004)	0.016*** (0.004)	0.016*** (0.004)	0.016*** (0.004)	0.016*** (0.004)
Paleo-temperature (mean) (t-1)		-0.261*** (0.015)	-0.253*** (0.015)	-0.259*** (0.016)	-0.257*** (0.016)
Paleo-precipitation (mean) (t-1)		0.058*** (0.020)	0.052** (0.021)	0.030 (0.020)	0.030 (0.020)
Paleo-temperature (std.) (t-1)			0.019*** (0.004)	0.023*** (0.004)	0.023*** (0.004)
Paleo-precipitation (std.) (t-1)			0.026** (0.011)	0.031*** (0.012)	0.030*** (0.012)
Paleo-net primary productivity (mean) (t-1)				0.040** (0.017)	0.041** (0.017)
Paleo-net primary productivity (std.) (t-1)				0.008 (0.007)	0.012 (0.008)
Paleo-ecological diversity (t-1)					-0.008* (0.004)
Outcome mean	0.002	0.002	0.002	0.002	0.002
Cell FE	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓
Adjusted R-Sqr.	0.028	0.028	0.029	0.029	0.029
Observations	319447	319447	319447	319447	319447

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 emergence of agriculture and 0 otherwise. The panel spans from 22,000 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 F14: Robustness to intermonthly temperature volatility and climatic seasonality (independent transition)

	Neolithic Revolution indicator									
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS	(9) OLS	(10) OLS
Lost biomass (t-1)	0.015*** (0.004)	0.016*** (0.004)	0.016*** (0.004)	0.016*** (0.004)	0.016*** (0.004)	0.014*** (0.005)	0.016*** (0.005)	0.016*** (0.005)	0.015*** (0.005)	0.015*** (0.005)
Intermonthly temperature vol. (t-1)	1.042*** (0.096)	0.867*** (0.091)	0.923*** (0.094)	0.891*** (0.097)	0.894*** (0.097)					
Intermonthly temperature vol. sqr. (t-1)	-1.029*** (0.073)	-0.705*** (0.068)	-0.736*** (0.069)	-0.714*** (0.072)	-0.715*** (0.072)					
Temperature (seasonality) (t-1)						-0.096*** (0.013)	-0.028** (0.014)	-0.026* (0.014)	-0.030** (0.014)	-0.030** (0.014)
Precipitation (seasonality) (t-1)						0.051*** (0.008)	0.016* (0.008)	0.015* (0.008)	0.019** (0.008)	0.018** (0.008)
Paleo-temperature (mean) (t-1)		-0.222*** (0.023)	-0.214*** (0.023)	-0.219*** (0.023)	-0.218*** (0.023)		-0.262*** (0.021)	-0.254*** (0.021)	-0.265*** (0.022)	-0.263*** (0.022)
Paleo-precipitation (mean) (t-1)		0.056** (0.022)	0.047** (0.022)	0.031 (0.022)	0.032 (0.022)		0.053** (0.027)	0.044 (0.027)	0.009 (0.025)	0.009 (0.026)
Paleo-temperature (std.) (t-1)			0.029*** (0.005)	0.031*** (0.005)	0.031*** (0.005)			0.021*** (0.005)	0.027*** (0.005)	0.027*** (0.005)
Paleo-precipitation (std.) (t-1)			0.034*** (0.011)	0.036*** (0.012)	0.036*** (0.012)			0.027* (0.014)	0.035** (0.015)	0.035** (0.015)
Paleo-net primary productivity (mean) (t-1)				0.030* (0.018)	0.030* (0.018)				0.071*** (0.021)	0.071*** (0.021)
Paleo-net primary productivity (std.) (t-1)				0.010 (0.007)	0.013* (0.008)				0.014 (0.009)	0.016* (0.009)
Paleo-ecological diversity (t-1)					-0.009* (0.005)					-0.006 (0.005)
Outcome mean	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Adjusted R-Sqr.	0.030	0.030	0.030	0.030	0.030	0.033	0.034	0.034	0.034	0.034
Observations	295031	295031	295031	295031	295031	254431	254431	254431	254431	254431

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 emergence of agriculture and 0 otherwise. The panel spans from 22,000 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 F15: Horse-race regression: lost biomass vs. extinction rate in explaining independent transitions (cross-grid-cell)

	Indicator of the Neolithic Revolution						
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS
Lost biomass	0.03*** (0.00)		0.05*** (0.01)	0.05*** (0.01)	0.05*** (0.01)	0.05*** (0.01)	0.05*** (0.01)
Extinction rate		0.01 (0.02)	-0.09*** (0.02)	0.02 (0.03)	0.01 (0.03)	0.01 (0.03)	0.02 (0.03)
Extinction rate (sqr.)		0.01 (0.02)	0.06*** (0.02)	-0.05 (0.03)	-0.04 (0.03)	-0.04 (0.03)	-0.04 (0.03)
Paleo-temperature (mean)					0.01 (0.02)	0.01 (0.02)	0.03 (0.03)
Paleo-precipitation (mean)					-0.02** (0.01)	-0.03*** (0.01)	-0.03*** (0.01)
Paleo-temperature (std.)					-0.00 (0.00)	-0.00 (0.00)	-0.00 (0.00)
Paleo-precipitation (std.)					0.01 (0.01)	0.01 (0.01)	0.01* (0.01)
Paleo-net primary productivity (mean)						0.01 (0.01)	0.02 (0.01)
Paleo-net primary productivity (std.)						0.00 (0.00)	0.00 (0.00)
Paleo-ecological diversity						-0.00 (0.00)	0.00 (0.00)
Outcome mean	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Continent FE	✓	✓	✓				
Block FE (10° × 10°)				✓	✓	✓	✓
Geographical controls							✓
Observations	14270	14270	14270	14270	14270	14270	14270

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 emergence of agriculture and 0 otherwise. Geographical controls include absolute latitude, the mean and standard deviation of land suitability for agriculture, terrain ruggedness, land area, the log distant to the nearest waterway. All variables are standardized. Robust standard errors, clustered using the spatial correlation proposed by Conley (1999) with a threshold of 200 km, are reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table F16: 2SLS, first-stage, and reduced-form regressions: lost biomass vs. extinction rate in explaining independent transitions (grid-cell panel)

	Panel A: second-stage The NR indicator				Panel B: first-stage Lost biomass (t-1)				Panel C: reduced form The NR indicator			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	2SLS	2SLS	2SLS	2SLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS
Lost biomass (t-1)	0.554*** (0.057)	0.512*** (0.056)	0.523*** (0.056)	0.508*** (0.053)								
Lost biomass (IV) (t-1)					3.044*** (0.109)	3.032*** (0.108)	3.017*** (0.109)	3.181*** (0.111)	1.685*** (0.167)	1.554*** (0.165)	1.579*** (0.165)	1.617*** (0.165)
Extinction rate (t-1)	-0.705*** (0.071)	-0.652*** (0.069)	-0.666*** (0.070)	-0.648*** (0.067)	1.221*** (0.029)	1.221*** (0.029)	1.221*** (0.029)	1.225*** (0.030)	-0.030*** (0.005)	-0.026*** (0.005)	-0.027*** (0.005)	-0.026*** (0.005)
Extinction rate sqr. (t-1)	0.249*** (0.032)	0.230*** (0.031)	0.235*** (0.031)	0.230*** (0.030)	-0.437*** (0.039)	-0.437*** (0.039)	-0.437*** (0.039)	-0.440*** (0.039)	0.007* (0.004)	0.006 (0.004)	0.007 (0.004)	0.006 (0.004)
Paleo-temperature (mean) (t-1)		-0.238*** (0.016)	-0.228*** (0.016)	-0.219*** (0.017)		-0.022*** (0.008)	-0.020** (0.009)	-0.049*** (0.009)		-0.249*** (0.016)	-0.238*** (0.016)	-0.244*** (0.017)
Paleo-precipitation (mean) (t-1)		0.039* (0.023)	0.029 (0.023)	0.061*** (0.023)		0.004 (0.010)	0.009 (0.010)	-0.100*** (0.012)		0.041* (0.023)	0.033 (0.023)	0.011 (0.022)
Paleo-temperature (std.) (t-1)			0.021*** (0.006)	0.017*** (0.006)			0.007 (0.008)	0.024*** (0.008)			0.025*** (0.005)	0.029*** (0.005)
Paleo-precipitation (std.) (t-1)			0.043*** (0.012)	0.032** (0.013)			-0.029*** (0.006)	0.000 (0.007)			0.028** (0.012)	0.032** (0.013)
Paleo-net primary productivity (mean) (t-1)				-0.056*** (0.020)				0.197*** (0.009)				0.044*** (0.017)
Paleo-net primary productivity (std.) (t-1)				0.005 (0.008)				0.019*** (0.004)				0.015* (0.008)
Paleo-ecological diversity (t-1)				-0.009** (0.005)				0.003 (0.003)				-0.008* (0.005)
Outcome mean	0.002	0.002	0.002	0.002	0.039	0.039	0.039	0.039	0.002	0.002	0.002	0.002
Cell FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
First stage F	775.872	781.921	770.715	823.060								
Adjusted R-Sqr.					0.541	0.541	0.541	0.542	0.030	0.031	0.031	0.031
Observations	288340	288340	288340	288340	288340	288340	288340	288340	288340	288340	288340	288340

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 emergence of agriculture and 0 otherwise. The panel spans from 22,000 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 F17: 2SLS, first-stage, and reduced-form regressions: lost biomass vs. extinction rate in explaining independent transitions (cross-grid-cell)

	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	0.058*** (0.007)	0.076*** (0.011)	0.055*** (0.010)	0.060*** (0.010)								
Lost biomass (IV)					0.636*** (0.015)	0.496*** (0.016)	0.528*** (0.018)	0.519*** (0.018)	0.037*** (0.004)	0.037*** (0.005)	0.029*** (0.005)	0.031*** (0.005)
Extinction rate		-0.144*** (0.020)	-0.077*** (0.028)	-0.081*** (0.030)		1.459*** (0.030)	1.296*** (0.047)	1.299*** (0.051)		-0.034** (0.017)	-0.005 (0.023)	-0.003 (0.025)
Extinction rate (sqr.)		0.089*** (0.019)	0.036 (0.026)	0.044 (0.027)		-0.819*** (0.029)	-0.650*** (0.043)	-0.648*** (0.046)		0.027 (0.020)	0.001 (0.025)	0.006 (0.026)
Paleo-temperature (mean)			0.015** (0.007)	-0.005 (0.011)			-0.033 (0.021)	-0.083*** (0.030)			0.013* (0.008)	-0.010 (0.011)
Paleo-precipitation (mean)			-0.027** (0.011)	-0.036*** (0.011)			-0.017 (0.024)	-0.014 (0.024)			-0.028*** (0.011)	-0.037*** (0.011)
Paleo-temperature (std.)			0.006 (0.004)	0.001 (0.004)			0.035*** (0.010)	0.027*** (0.010)			0.008* (0.004)	0.003 (0.004)
Paleo-precipitation (std.)			0.015** (0.008)	0.016** (0.007)			0.003 (0.011)	0.002 (0.011)			0.016** (0.007)	0.016** (0.007)
Paleo-net primary productivity (mean)			0.030** (0.012)	0.028** (0.012)			-0.048** (0.023)	-0.057** (0.023)			0.027** (0.012)	0.025** (0.012)
Paleo-net primary productivity (std.)			0.004 (0.005)	0.004 (0.005)			-0.051*** (0.008)	-0.055*** (0.008)			0.001 (0.005)	0.001 (0.005)
Paleo-ecological diversity			-0.007* (0.004)	-0.004 (0.004)			0.047*** (0.010)	0.044*** (0.009)			-0.005 (0.004)	-0.001 (0.004)
Outcome mean	0.044	0.044	0.044	0.044	0.499	0.499	0.499	0.499	0.044	0.044	0.044	0.044
Block FE (10° × 10°)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Geographical controls				✓				✓				✓
First stage F	1687.163	1009.296	847.092	813.997								
Observations	14270	14270	14270	14270	14270	14270	14270	14270	14270	14270	14270	14270

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 emergence of agriculture and 0 otherwise. Geographical controls include absolute latitude, the mean and standard deviation of land suitability for agriculture, terrain ruggedness, land area, the log distant to the nearest waterway. All variables are standardized. Robust standard errors, clustered using the spatial correlation proposed by Conley (1999) with a threshold of 200 km, are reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table F18: 2SLS: Heterogeneity with respect to agricultural suitability (independent transition)

	Neolithic Revolution indicator				
	(1) 2SLS	(2) 2SLS	(3) 2SLS	(4) 2SLS	(5) 2SLS
Lost biomass (t-1)	1.788*** (0.405)	2.120*** (0.425)	2.109*** (0.424)	1.768*** (0.460)	1.765*** (0.460)
Lost biomass (t-1) \times land suitability dummy	2.646*** (0.362)	1.524*** (0.409)	1.593*** (0.410)	2.042*** (0.524)	2.048*** (0.524)
Paleo-temperature (mean) (t-1)		-0.334*** (0.022)	-0.333*** (0.022)	-0.323*** (0.023)	-0.320*** (0.023)
Paleo-precipitation (mean) (t-1)		0.154*** (0.027)	0.152*** (0.027)	0.183*** (0.032)	0.184*** (0.032)
Paleo-temperature (std.) (t-1)			0.002 (0.005)	0.000 (0.005)	0.000 (0.005)
Paleo-precipitation (std.) (t-1)			0.024** (0.011)	0.015 (0.012)	0.015 (0.012)
Paleo-net primary productivity (mean) (t-1)				-0.043* (0.023)	-0.043* (0.023)
Paleo-net primary productivity (std.) (t-1)				0.003 (0.007)	0.009 (0.008)
Paleo-ecological diversity (t-1)					-0.012*** (0.004)
Outcome mean	0.002	0.002	0.002	0.002	0.002
Cell FE	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓
First stage F	433.219	486.474	488.423	653.481	653.110
Observations	306630	306630	306630	306630	306630

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 emergence of agriculture and 0 otherwise. The land suitability dummy equals 1 if a grid cell's land suitability for agriculture exceeds the median value, and 0 otherwise. The panel spans from 22,000 BP until the transition occurs, using 1,000-year time windows. All variables except for lost biomass (t-1) and its interaction with land suitability dummy are standardized. Robust standard errors, clustered at the grid cell level, are reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

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