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Agricultural transition and the adoption of primitive technology

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AGRICULTURAL TRANSITION AND THE ADOPTION OF PRIMITIVE TECHNOLOGY

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Abstract: This paper tests Jared Diamond's influential theory that an earlier transition from a hunter-gatherer society to agricultural production induces higher levels of technology adoption. Using a proxy for the geographic diffusion barriers of Neolithic technology and an index of biogeographic endowments to isolate the exogenous component of the timing of agricultural transition, the findings indicate that countries that experienced earlier transitions to agriculture were subsequently more capable of adopting new technologies in 1000 BC, 1 AD and 1500 AD. These results lend strong support to Diamond's hypothesis.

Key words: technology adoption; agricultural transition; early economic development.
JEL classification: O30; O40

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1. INTRODUCTION

Technology is the centrepiece of the literature on economic growth (Nelson and Phelps, 1966; Aghion and Howitt, 1992, 2009; Mokyr, 1990, 2005; Jones, 1995; Hsieh and Klenow, 2010). Surprisingly, little is known about what causes the wide disparity in the adoption levels of technology across the globe. The importance of historical technology adoption for long-run comparative economic development has recently been highlighted in the seminal contribution of Comin *et al.* (2010). They construct indicators to capture the ancient state of technology adoption in 1000 BC, 1 AD and 1500 AD, and show that the historical levels of technology adoption of a country crucially determines its current technology adoption levels and per capita income. Comin and Hobijn (2010) provide further evidence that technology adoption lags explain more than 25 percent of per capita income differences across countries, thus suggesting that a longer lag significantly lowers present-day standards of living (see also Comin *et al.*, 2008). However, the issue of what accounts for differences in technology adoption levels across the world has so far not been addressed in the literature. Without a proper understanding of the sources of technology adoption, the history of economic development will remain incomplete.

A prominent explanation for the cross-country variations in technology adoption levels has been provided by Diamond (1997), who links early agrarian development to the capability of adopting new technology. The transition from a hunter-gatherer society to agricultural production, also known as the Neolithic Revolution that first occurred about 11 millennia ago, is one of the most significant events in human history (Putterman, 2008). The first Neolithic transition occurred in the Middle East, where there was a shift from hunting and gathering to the cultivation of crops and animals. Diamond (1997) argues that following this transition, food production was focused on domesticating rather than gathering wild plants and hunting animals. The capacity of the agriculture sector to yield more and better food, provide nourishment for more people and produce storable food led to the creation of a non-food production class. These specialists were responsible for the early development of writing, education, technology-based military expertise, and social and political structures, which subsequently played a pivotal role in technological development.

Along with this development, agricultural settlements also facilitated more sedentary living, which underlies the historical development of technology as it enabled the accumulation of technical know-how. This developmental head start, built upon the foundations established during the transition, enabled an economy to enter into the path of endogenous knowledge creation and lowered costs of adopting technologies, which subsequently translated into greater technological sophistication. Furthermore, significant improvements in farming techniques and the ensuing increases in agricultural productivity then partially contributed to the onset of the Industrial Revolution. Thus, Diamond's thesis proposes a fundamental link between an early start in agriculture and the subsequent sophistication in technology.

Against this backdrop, our aim is to shed some light on how the timing of agricultural transition affects technology adoption in different periods of human history. In order to provide a direct assessment for the hypothesis that the Neolithic transition triggered the emergence of a long lasting endogenous knowledge creation process, leading to increased levels of technological development, variations in the onset of agricultural transition across countries is used to capture the extent of the developmental head start during the agricultural stage of development (see Ashraf *et al.*, 2010; Ashraf and Galor, 2011).

A major challenge in estimating the causal influence of agricultural transition is that it may be endogenous with respect to technology adoption. That is, the estimates may be biased due to reverse causation, measurement errors or omitted variables, and thus cannot be interpreted as reflecting a causal effect of agricultural transition on technology adoption. In order to isolate the exogenous variation in the timing of agricultural transition, geographic distance to the Neolithic point of origin and an index of biogeographic endowments are used as instruments. The choice of the first instrument is based on the reasoning that countries located in close proximity to the Neolithic cores tend to have similar cultural, ecological and geographic conditions, and thus enjoy a lower imitation cost. Faced with lower adoption barriers, this enabled them to absorb the diffusions of the point of origin's technology more effectively. Initial conditions of biogeography may serve as another appropriate instrument for the timing of transition to agriculture on the grounds that countries endowed with a greater variety of prehistoric wild plants and animals suitable for domestication were able to experience agricultural settlements earlier than others.

In line with common practice in the literature, we control for various effects of geography. Regional dummies, which are classified according to how Neolithic farming techniques spread across borders within the same agricultural spread zones, are also included in the regressions to remove the effects of regional specific unobserved heterogeneity bias. Using the datasets of Comin *et al.* (2010) for the levels of technology adoption and the agricultural transition timing estimates of Putterman (2006), our results indicate that countries that experienced an earlier transition to sedentary agriculture were technologically more sophisticated in 1000 BC . The economic effect of the timing of agricultural transition is found to be very large, and this variable turns out to be the most significant contributor to the levels of technology adoption among all variables included in the regressions. The timing of transitions to sedentary agriculture is also found to have a significant influence on technology adoption in 1 AD and 1500 AD, although the size of this impact is much smaller. These results prevail even if we control for the extent of state presence, genetic distance relative to the technological frontier and demographic pressure. Overall, the results provide significant evidence supporting the hypothesis of Diamond (1997).

This paper is closely related to a growing literature on how early development affects various economic outcomes. For instance, Chanda and Putterman (2007) and Putterman (2008) show that an earlier start of agriculture helps predict the variations in income in 1500 AD, a result that lends support to the prediction of Diamond (1997). Others have found that such an effect persists until today. In particular, the recent empirical work of Ashraf *et al.* (2010), Putterman and Weil (2010) and Bleaney and Dimico (2011) corroborate the above findings by uncovering a statistically robust positive effect of the onset of the Neolithic Revolution on current levels of income. In line with this, a highly cited contribution by Olsson and Hibbs (2005) demonstrates that countries with favourable prehistoric biogeographic endowments, which subsequently induced an earlier transition to agriculture, tend to have a higher level of income today. In this connection, it is worth mentioning that a recent study by Olsson and Paik (2013) documents a negative correlation between years since agricultural transition and current income levels in the Western countries. The underlying reason for this reversal pattern, however, remains unclear.

Some authors have also examined the impact of the Neolithic transition on other economic outcomes such as income inequality (Putterman and Weil, 2010), population density (Özak, 2011), institutions (Ang, 2013), and the length of state history (Ang, 2014). Nevertheless, despite significant efforts having been made to understand the impact of agricultural transition, a key premise underlying the theory that an earlier transition directly contributes to subsequent technological development has remained untested.

The paper proceeds as follows. The next section sets out the empirical framework and explains the identification strategy. It also describes the data and construction of variables. A list of variables with its definitions and sources are given in the appendix. Section 3 presents and analyses the empirical findings and provides several robustness checks. Some additional analyses are performed in Section 4. The last section concludes.

2. EMPIRICAL STRATEGY AND DATA

2.1 Regression model

The following regression model is considered to evaluate the impact of the timing of agricultural transition on the levels of technology adoption in the ancient and pre-modern times:

$$Tech.adop._i = \alpha + \beta Yrs\ since\ agr.tran._i + \gamma' Controls_i + \varepsilon_i \tag{1}$$

where $Tech.adop.$ is the levels of technology adoption representing the state of technological development in 1000 BC, 1 AD and 1500 AD; $Yrs\ since\ agr.tran.$ refers to the number of years elapsed since the transition to agriculture was estimated to have occurred; $Controls$ is a vector of variables controlling for various geographic effects, as described below; and ε is the error term. We are mainly interested in the sign, size, and significance of β. Eq. (1) will be estimated with and without control variables to check if the results are sensitive to their inclusion. Our sample consists of 103 countries, covering the following five macro-regions: Africa, Eurasia, Oceania, North America and South America. Since the timing of agricultural transition could reflect some regional effects, region dummies based on this classification are also included in all regressions to ensure that the results are not distorted by the potential influence of some unobserved regional specific heterogeneous effects.

Diamond's (1997) hypothesis emphasizes that several geographical antecedents, in particular, climate conditions, the orientation of axis, and the size of landmasses are fundamental for agricultural transition to occur. First, a temperate climate is conducive for agricultural development. The Mediterranean climate of Eurasia, for example, is particularly suitable for the cultivation of certain crops, providing favourable conditions for agricultural settlements. Second, greater East-West rather than North-South orientation facilitates the diffusion and adoption of farming techniques across regions. Areas along the same latitude tend to have certain ecological conditions which are similar, which enable newly arrived domesticated plants and animals to adapt easily to the new environments. Third, a bigger landmass implies greater biogeographic diversity, and this provides more potential domesticates for foragers enabling them to settle. Controlling for these geographical antecedents is not only consistent with the prediction of Diamond’s thesis but also allows for the possibility that they may continue to exert an influence on technology adoption, even after the occurrence of agricultural transition.

Following standard practice in the literature, the regressions also include latitude, landlocked dummy, island dummy and terrain ruggedness as additional control variables since they may be potentially important in explaining the heterogeneity of technology adoption levels across the world in the ancient and pre-modern times, given that poor and technologically backward countries tend to share certain geographic characteristics. More specifically, these geographic features may determine the quality of soil, stability of rainfall, disease environment, endowment of natural resources, transport costs and ability to diffuse technology, all of which tend to influence technological development via agricultural productivity (see, e.g., Sachs, 2001; Rodrik *et al.*, 2004).

2.2 Identifying the causal effect of agricultural transition

Eq. (1) can be estimated using the OLS estimator. However, we cannot rule out the possibilities that the timing of transition is subject to reverse causality, the association between technology adoption and agricultural transition is spurious due to the failure to account for some unobserved channels such as human capital, language, climate change, and depletion of natural resources which are related to both variables, or that the estimated transition dates are subject to some measurement errors, all of which will violate the standard OLS assumptions. Accordingly, in order to estimate the causal effect of agricultural transition on technology adoption, we use a proxy for the diffusion barriers of Neolithic technology and an index of biogeographic endowments as the instruments for the timing of agricultural transition.

The diffusion barriers of Neolithic technology are captured by the geographic distance between a society and its closest regional Neolithic point of origin. Technology diffusions often occur through the channels of trade, espionage, emigration, war, and subjugation, and their intensity is strongly influenced by the proximity between societies (Cavalli-Sforza, 2000). Societies located closer to the agricultural pristine sources are likely to face less cultural, ecological or geographic barriers to diffusion (Özak, 2010), thus facilitating the spread and adoption of the Neolithic technologies. For instance, the earliest Neolithic period began in the Middle East more than 10,000 years ago. Agricultural innovation spread relatively easily from the Middle East to its neighboring countries in Europe, Egypt, India, Iran, and Pakistan (Cavalli-Sforza, 2000). Archaeological data also provide evidence that early farming and adoption of Neolithic tools in Southeast Asia were strongly connected with its regional source, China (Bellwood, 2005). New crops and farming techniques from China reached the Southeast countries easily due to their geographic and ecological similarity. That proximity matters for

Neolithic diffusion is also evidenced by the fact that it took only 200 years for farming to spread from Italy to Portugal, but 1000 years from the Philippines to Samoa (Bellwood, 2005, p. 276).

Findings by two recent studies further support the use of diffusion barriers of Neolithic technology as an instrument for the timing of agricultural transition. In particular, Baker (2008) develops a model of agricultural transition and provides evidence showing that societies located further away from the pioneer of agricultural settlement, the Fertile Crescent, tend to experience a later date of farming transition. Along similar lines, the empirical results of Ashraf and Michalopoulos (2014) demonstrate that distance from the nearest Neolithic point of origin, a proxy we use for the diffusion barriers of Neolithic technology, exerts a negative influence on the timing of transition to agriculture, both across countries and across Neolithic sites.

Additionally, the occurrence of agricultural transition may be precipitated by other factors apart from the spread of farming techniques. Ammerman and Cavalli-Sforza (1984) and Diamond (1997) argue that countries endowed with more prehistoric wild plants suitable for cultivation, and wild animals suitable for domestication were able to transit from the hunter-gatherer lifestyle to agriculture earlier than others and hence the initial conditions of biogeography influenced the timing of the transition. To the extent that biogeographic endowments triggered the onset of agricultural transition and yet are unlikely to be directly related to technology adoption, the first principal component of the number of wild animals and plants suitable for domestication prior to the onset of the Neolithic Revolution is an appropriate instrument to obtain the exogenous sources of variation for agricultural transition. This approach is consistent with the empirical strategy of Ashraf and Galor (2011).

Accordingly, in the instrumental variable regressions, the timing of Neolithic transition is treated as endogenous and the equation of agricultural transition is specified as follows:

$$Yrs\ since\ agr.tran._i = \pi + \rho_1 DTNO_i + \rho_2 BIOGEO_i + \sigma' Controls_i + \mu_i \tag{2}$$

where $DTNO$ is a measure of the distance to the Neolithic point of origin (i.e., “as the crow flies” distance between a particular country and the nearest country located within its original Neolithic site), $BIOGEO$ is an index of biogeographic endowments, and μ is the residual. In this case, the variation in agricultural transition timing that is exogenous due to the diffusion barriers of Neolithic technology and the initial biogeographic conditions will be isolated by $DTNO$ and $BIOGEO$, respectively, from the endogenous variation in agricultural transition timing due to the unobserved error term. Our identification strategy will be valid so long as $DTNO$ and $BIOGEO$ are uncorrelated with the residuals. In other words, under the assumption that the diffusion barriers of agricultural know-how and biogeographic conditions do not affect technology adoption directly, other than through the timing of the occurrence of the Neolithic transition, conditional on the controls included in the regressions, this exclusion restriction is an appropriate strategy for identifying the channel of influence. In econometric terms, $DTNO$ and $BIOGEO$ are strong instruments, as demonstrated by the satisfactory first-stage partial R-squared values and F-statistics for the excluded instruments (see the instrumental variable estimates reported in Table 3).

2.3. Data

(a) Technology adoption

Comin *et al.* (2010) provide data on technology adoption levels, which reflect whether a particular technology was in use at different points in time, i.e., 1000 BC, 1 AD and 1500 AD. The datasets cover technologies in use in the following five sectors: 1) agriculture; 2) transportation; 3) communications; 4) industry; and 5) military. The total number of state-of-the-art technologies covered in the above sectors is 12 for 1000 BC and 1 AD, and 24 for 1500 AD. Equal weights have been assigned to all sectors so that technologies in use in any particular sector do not dominate the others. The average level of adoption is first calculated for each sector, and the overall adoption level is the average level of adoption for all sectors. The resulting indices, with values ranging between 0 and 1, provide an indication of the overall level of technology adoption in 1000 BC, 1 AD, and 1500 AD. Specifically, a value of 1 indicates full adoption of all technologies considered by Comin *et al.* (2010) whereas 0 means no adoption of any of the technologies.

Table 1: Descriptive statistics

Variable	Obs.	Mean	Std. Dev.	Min.	Max.
Technology adoption in 1000 BC (index)	82	0.43	0.29	0.00	1.00
Technology adoption in 1 AD (index)	101	0.72	0.29	0.00	1.00
Technology adoption in 1500 AD (index)	89	0.48	0.32	0.00	1.00
Years of agricultural transition (1000 years)	103	4.42	2.33	0.40	10.50
Distance to the Neolithic point of origin (100 km)	103	21.21	16.58	0.00	111.77
Biogeography (standardized values)	103	0.04	1.01	-0.95	1.48
Climate classification	103	2.60	1.05	1.00	4.00
Axis (ratio)	103	1.55	0.68	0.50	3.00
Landmass size (millions of square)	103	30.08	14.21	0.00	44.61
Absolute latitude	103	0.29	0.19	0.01	0.71
Landlocked (dummy)	103	0.23	0.42	0.00	1.00
Island (dummy)	103	0.08	0.27	0.00	1.00
Terrain ruggedness (index)	103	1.24	1.10	0.02	6.20

Notes: refer to the text or Table A1 in the appendix for descriptions of all variables.

The summary statistics presented in Table 1 indicate that the average level of technology adoption was significantly higher in 1 AD (0.72) compared to that in 1000 BC (0.43). The average adoption level in 1500 AD was only 0.48. It should be noted, however, that the estimates for 1 AD and 1000 BC are not directly comparable to those of 1500 AD due to the use of different coding procedures for different sources which involve different types of technologies used. Military, for instance, indicates the adoption of stone, bronze or iron tools in the 1000 BC and 1 AD datasets but refers to the presence of standing armies, cavalry, firearms, warfare capable ships etc. in the 1500 AD dataset. If the additional technologies considered were relatively new at the time when they were introduced in 1500 AD, it is not surprising that the data show a lower level of adoption. This issue is not particularly concerning, however, given the fact that our estimation focuses on cross-country differences rather than variations in the time series of the data. Nevertheless, to facilitate the comparison of estimates, we also report the beta coefficients of agricultural transition in all the main tables.

(b) Agricultural transition

Data for the timing of agricultural transition are obtained from Putterman (2006). The years of agricultural transition reflect the estimated number of years since the transition has occurred. Therefore, a higher value implies an earlier transition. These estimates cover a time span of more than 10 millennia, starting from 8,500 BC to the present day, circa 2000 AD. According to Putterman (2006), the transition years are estimated based on the first year in which more than half of a human’s calorific needs were obtained from cultivated plants and domesticated animals. In our sample of 103 countries, the transition to agriculture is estimated to have first occurred in Israel, Jordan and Syria (10,500 years ago) and last occurred in Australia (400 years ago). Figure 1 presents the distribution of the estimated agricultural transition dates across the globe using data for all available countries from Putterman (2006).

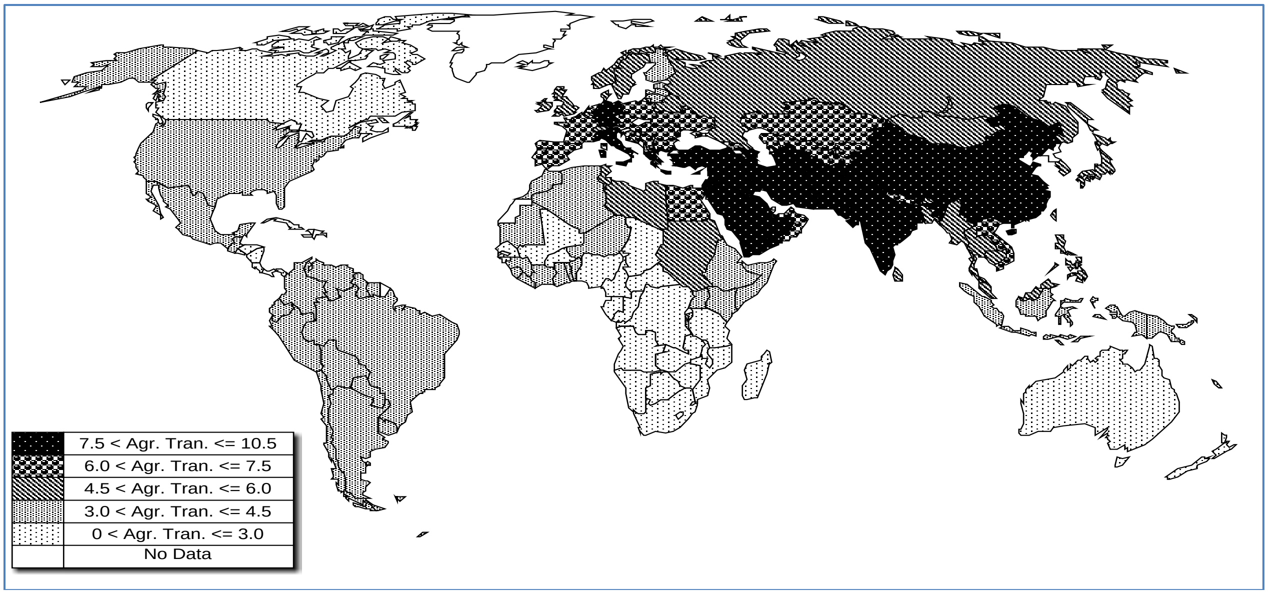
(c) Distance to the Neolithic point of origin

We construct the geographical distance between a particular country and its original source of Neolithic technology as a proxy for the geographical diffusion barriers of Neolithic technology. Using details provided by Diamond (1997), Diamond and Bellwood (2003) and Bellwood (2005), the following six major centers of agricultural origin are considered (the approximate date in which farming was spread is indicated in the bracket): 1) Fertile Crescent (11,000 BP); 2) Yangzi and Yellow River Basins (9,000 BP); 3) New Guinea Highlands (9,000-

6,000 BP); 4) Central Mexico (5,000-4,000 BP); 5) Northern South America (5,000-4,000 BC); and 6) West Africa, the Sahel and Ethiopian highland (5,000-4,000 BP) (see Table A2 and Figure 1A in the appendix for more details).

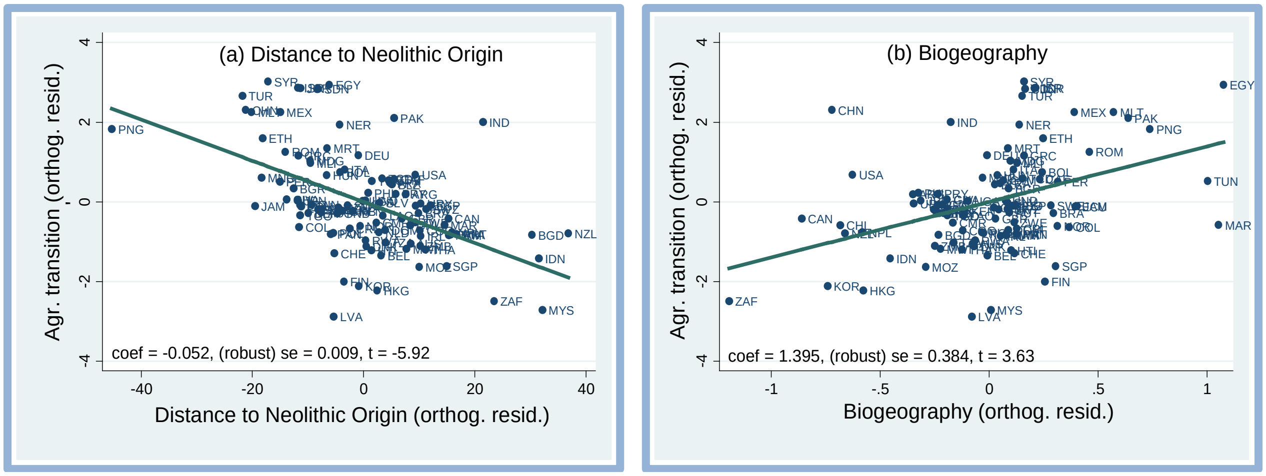
Specifically, we first classify all countries in our sample into the following agricultural spread zones with their respective Neolithic centers indicated in brackets: North America (Central Mexico), South America (Northern South America), Sub-Saharan Africa (West Africa and Ethiopian Highland), Middle East and North Africa (Fertile Crescent), South Asia (Fertile Crescent), Europe and Central Asia (Fertile Crescent), East Asia (Yangzi and Yellow River Basins), Oceania excluding Papua New Guinea (Yangzi and Yellow River Basins), and Papua New Guinea (New Guinea Highlands). Figure A1 provides the details. For example, Belgium is assumed to have received its agriculture from the Fertile Crescent, which is defined to include the modern-day territories of Iraq, Syria and Turkey (see Table A2). Then Belgium's distance to its Neolithic point of origin is taken to be "as the crow flies" distance between the center points of Belgium and the country nearest to Belgium within the group of countries comprising the Fertile Crescent, i.e., Turkey. The distance is calculated using the 'Haversine' formula, which measures the shortest distance between two countries on the surface of the globe using the longitudes and latitudes of their center points.

Figure 1: Distribution of years since agricultural transition across 164 countries



Notes: the data show, in 2000 AD, how many thousands of years ago the transition to agriculture was estimated to have occurred. Darker areas represent an earlier transition date to sedentary agriculture and blank areas indicate no data are available. The data are obtained from Putterman (2006).

Figure 2: The relationships between agricultural transition and its instruments



Notes: the partial regression line in diagrams (a) and (b) illustrate the influence of distance to the Neolithic origin and biogeography, respectively, on agricultural transition dates while partialing out the effects of all other control variables. The number of observations is 103 for both diagrams.

The partial regression line in Figure 2(a) shows the effect of distance to the Neolithic core on agricultural transition after removing the influence of geographic controls and region dummies. As expected, the diagram depicts a negative relationship between these variables. This is consistent with the notion that countries in the neighbourhood of a Neolithic center could better adopt and assimilate the technologies from the pristine source, thus experiencing an earlier transition. Conversely, countries located far from their Neolithic center tend to have relatively late transitions to agriculture.

(d) Biogeography

The extent of prehistoric biogeographic endowments is measured by the first principal component of the standardized numbers of locally available domesticable wild animals (14 species in total) and plants (33 species in total) about 12,000 years ago, which are edible to humans or carry economic values, based on the data of Olsson and Hibbs (2005). Domesticable plants refer to the number of annual or perennial prehistoric wild grasses with a mean kernel weight greater than 10 mg (e.g., the ancestors of barley, rice, corn, wheat); domesticable animals denote the number of prehistoric mammals with weights exceeding 45 kg. They are the ancient ancestors of the following 14 domesticable animals: sheep, goats, cows, pigs, horses, Arabian camels, Bactrian camels, llama, donkeys, reindeer, water buffalo, yak, Bali cattle, and Mithan (Olsson and Hibbs, 2005).

Archaeological evidence suggests that the ancestors of wheat, peas, olives, sheep, and goats, for instance, were domesticated in the Fertile Crescent as early as 8,500 BC. Ancestors of rice, millet, and pigs were domesticated nearly as early, in China in 7,500 BC (Diamond, 1997). The distribution of plant and animal domesticates was very uneven across regions. Compared to the Pacific Islands which had no species suitable for domestication circa 10,000 BC, Europe had a superior initial biogeographic condition with all the 33 plant species and 9 out of 14 animal species considered in the dataset of Olsson and Hibbs (2005). Sub-Saharan Africa had access to 4 species of plants but had no access to any animals suitable for domestication, whereas America had access to 11 and 1 species of domesticable plants and animals, respectively. Consistent with our prediction, the partial regression line shown in Figure 2(b) confirms that the timing of agricultural transition and the index of biogeographic endowments are strongly and positively connected.

3. EMPIRICAL ESTIMATES

3.1 Least squares estimates

The regression results of Eq. (1) are presented in Table 2. Consider first the regressions for the basic model without the inclusion of control variables. The results indicate that agricultural transition is a significant determinant of the levels of technology adoption in 1000 BC, 1 AD and 1500 AD (columns (1a), (2a) and (3a)). This relationship is significant at the one percent level in all cases. The R-squared values imply that agricultural transition alone is able to explain between 57 and 83 percent of the variation in the levels of technology adoption across countries. Using the results in column 1(a) as an illustration, if a country transits to agriculture one thousand years earlier, the level of technology adoption is expected to be about 0.1 index points higher. Measured in standardized form, a one standard deviation change in agricultural transition is associated with 74.6 percent of a standard deviation change (beta coefficients) in the level of technology adoption in 1000 BC. These results imply a large economic effect of agricultural transition on technological development.

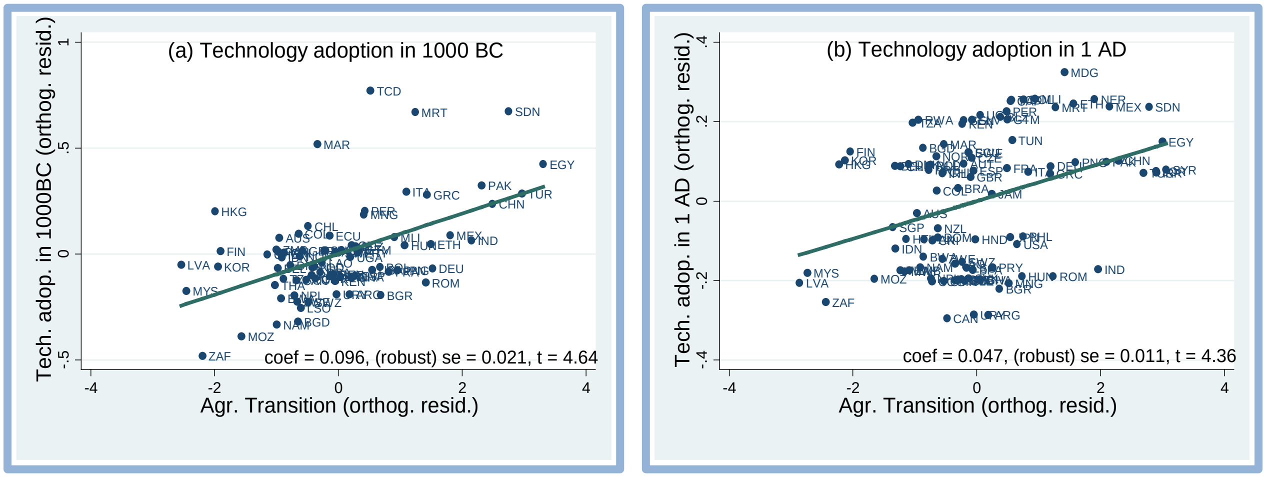
Interestingly, the size of the beta coefficients diminishes with the dates of technology adoption, implying that the effect of agricultural transition on technology adoption wane over time. In particular, the effect of agricultural transition on technology adoption reduces by more than 50 percent from 1000 BC to 1 AD. However, the reduction in the effect is only marginal from 1 AD to 1500 AD. The results prevail when all control variables are included in the unrestricted regressions (columns (1b), (2b) and (3b)). Graphical inspection on the partial regression lines for the effects of agricultural transition on technology adoption levels shown in Figures 3(a) to 3(c) are largely consistent with these findings.

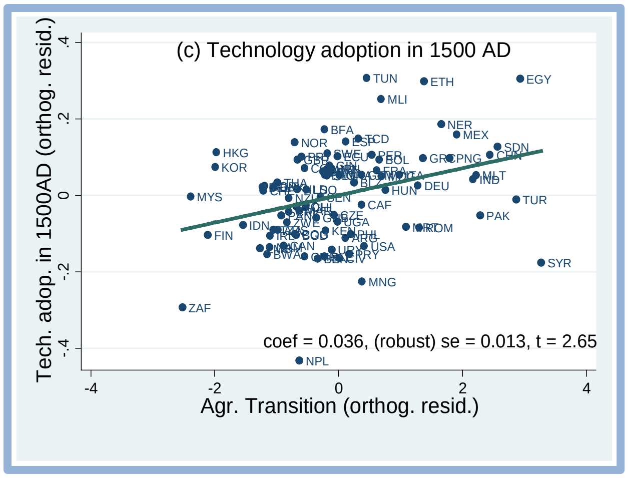
Table 2: Ordinary least squares estimates

Dep. Var. = *Tech. adop.*	(1a)	(1b)	(2a)	(2b)	(3a)	(3b)
	1000 BC	1000 BC	1 AD	1 AD	1500 AD	1500 AD
Yrs since agr. tran.	0.102***	0.096***	0.045***	0.047***	0.043***	0.035***
	(0.015)	(0.021)	(0.008)	(0.011)	(0.014)	(0.013)
[Beta coefficients]	[74.6%]	[69.8%]	[36.1%]	[38.3%]	[28.4%]	[23.6%]
Climate		-0.007		-0.006		0.055**
		(0.049)		(0.029)		(0.026)
Axis		0.033		-0.010		-0.002
		(0.060)		(0.028)		(0.037)
Landmass size		-0.000		-0.001		-0.001
		(0.002)		(0.001)		(0.001)
Latitude		0.101		0.127		0.075
		(0.197)		(0.160)		(0.121)
Landlocked		-0.090		-0.009		0.013
		(0.064)		(0.053)		(0.040)
Island		-0.180		-0.039		-0.005
		(0.162)		(0.060)		(0.048)
Terrain ruggedness		0.003		0.005		-0.017
		(0.022)		(0.017)		(0.016)
R-squared	0.572	0.594	0.698	0.703	0.832	0.862
Observations	82	82	101	101	89	89
Region dummies	Yes	Yes	Yes	Yes	Yes	Yes

Notes: the dependent variable is the levels of technology adoption in 1000 BC, 1 AD or 1500 AD. Figures in the parentheses are robust standard errors. ***, ** and * denote significance at the 1, 5 and 10 percent levels, respectively. The region dummies are Africa, Eurasia, Oceania, North America and South America. An intercept is included in the regressions but is not reported to conserve space.

Figure 3: Partial effects of the timing of agricultural transition on technology adoption levels





Notes: the scatter plots illustrate the influence of agricultural transition on technology adoption while partialing out the effects of all other control variables listed in Table 2. In other words, these partial regressions are based on the regressions of columns (1b), (2b) and (3b) in Table 2.

3.2 Two-stage least squares estimates

As highlighted before, to counteract potential bias from simultaneity, omitted variables and measurement error, Eq. (1) is also estimated using a two-stage least squared (2SLS) estimator with robust standard errors. The results presented in Table 3 show that the 2SLS estimates are qualitatively very similar to those that are based on the OLS estimator. Sizes of the coefficients of $Yrs\ since\ agr.tran.$ are in all cases considerably larger than those found earlier. This finding is consistent with the notion that the timing of agricultural transition is measured with errors rather than subject to simultaneity bias. The sign and size of the coefficients is quite stable across columns in each time period, implying that the relationship uncovered is not sensitive to the inclusion of control variables. Moreover, the explanatory power of the regressions involving control variables is similar to those that exclude them, suggesting that technology adoption levels are significantly influenced only by the dates of agricultural transition.

Using the estimates under column (1a) as a reference, an earlier transition to sedentary agriculture by 1000 years improves the state of technological development in 1000 BC by 0.142 index points. This magnitude suggests that agricultural transition has a rather significant economic impact on technological development in ancient times. For example, El Salvador had a rather late transition to agriculture which occurred approximately 3000 years ago and had a relatively low level of technology adoption of 0.3 in 1000 BC. If El Salvador had a more favourable environment that induced an earlier transition time, similar to that experienced in the Netherlands 6000 years ago, then El Salvador would become at least twice technologically more developed in 1000 BC. Its state of technological development would be 0.73, a level that exceeded the one that was enjoyed by the Netherlands in 1000 BC, i.e., 0.6.

Table 3: Instrumental variable regressions (baseline results)

Dep. Var. = Tech. adop.	(1a)	(1b)	(2a)	(2b)	(3a)	(3b)
	1000 BC	1000 BC	1 AD	1 AD	1500 AD	1500 AD
Panel A: 2nd-stage regressions						
Yrs since agr. tran.	0.142***	0.150***	0.071***	0.089***	0.080***	0.076***
	(0.024)	(0.035)	(0.014)	(0.022)	(0.020)	(0.022)
[*Beta coefficients*]	[103.6%]	[109.3%]	[57.5%]	[71.7%]	[53.0%]	[50.7%]
Climate		-0.040		-0.037		0.027
		(0.045)		(0.032)		(0.029)
Axis		0.070		-0.008		0.005
		(0.089)		(0.027)		(0.047)
Landmass size		-0.002		-0.002*		-0.002
		(0.004)		(0.001)		(0.001)
Latitude		0.268		0.269		0.188
		(0.242)		(0.181)		(0.156)
*Landlock*ed		-0.076		0.003		0.020
		(0.063)		(0.054)		(0.040)
Island		-0.063		0.016		0.043
		(0.216)		(0.063)		(0.064)
Terrain ruggedness		-0.001		0.004		-0.018
		(0.022)		(0.017)		(0.017)
R-squared	0.538	0.546	0.680	0.671	0.808	0.839
Panel B: 1st-stage regressions						
DTNO	-0.049***	-0.040***	-0.051***	-0.043***	-0.047***	-0.043***
	(0.008)	(0.012)	(0.009)	(0.010)	(0.008)	(0.011)
BIOGEO	0.827***	0.906*	0.897***	0.818**	0.881***	0.788**
	(0.297)	(0.462)	(0.222)	(0.367)	(0.219)	(0.365)
R-squared	0.757	0.786	0.770	0.803	0.776	0.799
Partial R-squared	0.397	0.311	0.426	0.314	0.450	0.366
F-test for excl. instruments	24.936	13.181	25.025	17.949	23.835	18.536
Robust score test for endogeneity	4.714** [p=0.029]	4.678** [p=0.031]	4.750** [p=0.029]	4.969** [p=0.026]	8.516*** [p=0.003]	9.475*** [p=0.002]
Observations	82	82	101	101	89	89
Region dummies	Yes	Yes	Yes	Yes	Yes	Yes

Notes: the dependent variable is the levels of technology adoption in 1000 BC, 1 AD or 1500 AD. The timing of agricultural transition is instrumented by distance to the Neolithic center (*DTNO*) and an index of biogeographic endowments (*BIOGEO*). The region dummies are Africa, Eurasia, Oceania, North America and South America. An intercept is included in the regressions but is not reported to conserve space. In the full specifications (all columns (b)), all control variables and region dummies are also included in the first-stage regressions. The F-test for excluded instruments tests the null hypothesis that the coefficients on the instruments equal zero in the first stage of the regressions. An F-statistic less than 10 indicates that the instruments are weak. The null for the robust score tests is that the timing of agricultural transition is exogenous. The results show Chi-square statistics and p-values (in square brackets). Figures in the round parentheses are robust standard errors. ***, ** and * denote significance at the 1, 5 and 10 percent levels, respectively.

The first-stage partial R-squared statistics measure the correlation between agricultural transition and its instruments, i.e., distance to the Neolithic point of origin and biogeographic endowments. A higher value indicates stronger instruments, implying that the estimates are less biased. These statistics, along with the large first-stage *F*-test statistics for the excluded instruments, which have their null hypothesis that the instruments do not explain cross-country variations in agricultural transition, provide credence that our instruments are strong in all cases. Furthermore, the robust score tests indicate that the null of agricultural transition being exogenous is rejected at conventional levels of significance for all models. Given these findings, the instrumental variable results reported in Table 3 will be used as the baseline estimates, and all subsequent analyses that follow will be benchmarked against them.

3.3 Sensitivity checks

This subsection performs several robustness checks for the instruments used. Following the format of the baseline estimates in Table 3, we provide results for technology adoption levels in 1000 BC, 1 AD and 1500 AD (columns (1), (2) and (3), respectively). Estimates without control variables are first presented (all columns (a)), followed by those with the inclusion of all control variables (all columns (b)). Region dummies are included in all regressions.

First, we consider an alternative approach to measuring the diffusion barriers of farming technology in which the Neolithic points of origin are determined by the countries in our sample that had the earliest dates of agricultural transition in each continent, as follows: Egypt and Libya (Africa); Mexico and Peru (America); Israel, Jordan, Lebanon and Syria (Asia); Cyprus and Greece (Europe); and New Zealand (Oceania). This classification of regions is based on the conventional approach rather than the macro spread zones used throughout the paper. The transition dates are based on the dataset of Putterman (2006).

Panel A of Table 4 presents the results based on these alternative estimates for distance to the Neolithic pristine sources. Consistent with the baseline results in Table 3, the timing of agricultural transition is found to have a positive impact on technology adoption levels in 1000 BC, 1 AD and 1500 AD, irrespective of whether control variables are included. In all cases, the parameter estimates of agricultural transition are very precisely estimated at the one percent level of significance. It should be noted that the regression results here are based on the use of spread zone dummies. The results are similar if the conventional continent dummies were used (unreported). Hence, the results are not sensitive to this alternative way of determining the agricultural cores.

Panels B to D consider alternative instruments but follow the baseline approach in assigning distance to agricultural cores. In panel B we report the estimates which use only distance to the Neolithic point of origin as the instrument. We repeat this exercise in panel C by considering only biogeography as the instrument. In both cases, the qualitative aspect of the results are very similar to those reported previously, suggesting that using only either one of these instruments does not bias our estimates. In panel D, we use the number of domesticable plants available and the number of domesticable animals available as instruments. The results, again, are largely invariant to this consideration. Overall, the results in Table 4 provide some evidence that our estimates are not sensitive to the consideration of these alternative instrumental variable strategies.

Table 4: Robustness checks using alternative instruments (IV-2SLS estimates)

$Dep.\ Var. = Tech.adop.$	(1a) 1000 BC	(1b) 1000 BC	(2a) 1 AD	(2b) 1 AD	(3a) 1500 AD	(3b) 1500 AD
Panel A: Choosing the agricultural cores by continent						
$Yrs\ since\ agr.tran.$	0.155***	0.168***	0.085***	0.109***	0.083***	0.063***
	(0.035)	(0.045)	(0.017)	(0.027)	(0.019)	(0.021)
R-squared	0.525	0.530	0.663	0.648	0.822	0.859
Observations	82	82	101	101	89	89
Instrument(s)	(i) Geographical distance to one of the countries that first transit to agriculture in each continent; (ii) biogeography index ($BIOGEO$)					
Panel B: Using only distance to the Neolithic center as the IV						
$Yrs\ since\ agr.tran.$	0.125***	0.125***	0.052***	0.065***	0.040**	0.059***
	(0.028)	(0.037)	(0.016)	(0.022)	(0.017)	(0.021)
R-squared	0.561	0.580	0.696	0.698	0.832	0.855
Observations	82	82	101	101	89	89
Instrument(s)	(i) Distance to the Neolithic point of origin ($DTNO$)					
Panel C: Using only biogeography as the IV						
$Yrs\ since\ agr.tran.$	0.178**	0.199**	0.108***	0.150***	0.144***	0.122***
	(0.071)	(0.080)	(0.030)	(0.049)	(0.039)	(0.040)
R-squared	0.450	0.417	0.593	0.507	0.645	0.756
Observations	82	82	101	101	89	89
Instrument(s)	(i) Biogeography index ($BIOGEO$)					
Panel D: Using the availability of plants and animals as IVs						
$Yrs\ since\ agr.tran.$	0.182**	0.206**	0.107***	0.149***	0.144***	0.118***
	(0.076)	(0.087)	(0.029)	(0.051)	(0.036)	(0.041)
R-squared	0.436	0.394	0.598	0.512	0.647	0.766
Observations	82	82	101	101	89	89
Instrument(s)	(i) Number of domesticable plants available; (ii) number of domesticable animals available					
Region dummies	Yes	Yes	Yes	Yes	Yes	Yes
Geographic controls	No	Yes	No	Yes	No	Yes

Notes: the dependent variable is the levels of technology adoption in 1000 BC, 1 AD or 1500 AD. The region dummies are Africa, Eurasia, Oceania, North America and South America. The geographic controls are climate, latitude, axis (the orientation of continent), size of landmass, landlocked dummy, island dummy, and terrain ruggedness. An intercept is included in the regressions but is not reported to conserve space. Figures in the parentheses are robust standard errors. ***, ** and * denote significance at the 1, 5 and 10 percent levels, respectively.

Next, we perform some additional robustness checks and report their results in Table 5. The technology adoption dataset used in this paper considers agriculture as one of the components of the overall level of technology adoption. To the extent that the agricultural component captures similar information to the timing of agricultural transition, its inclusion in the computation of the technology adoption level measures may generate some artificial correlations between the outcome variables and the agricultural transition timing measure. Consequently, in panel A, we exclude agriculture in the technology adoption measures but do not find any substantial qualitative variation in the results compared to the baseline estimates. Specifically, the parameter estimates of agricultural transition remain statistically highly significant in all cases.

Table 5: Other robustness checks (IV-2SLS estimates)

Dep. Var. = Tech. adop.	(1a) 1000 BC	(1b) 1000 BC	(2a) 1 AD	(2b) 1 AD	(3a) 1500 AD	(3b) 1500 AD
	Panel A: Considering non-agriculture technology adoption					
Yrs since agr. tran.	0.123^{***}	0.136^{***}	0.069^{***}	0.088^{***}	0.081^{***}	0.077^{***}
	(0.024)	(0.032)	(0.017)	(0.025)	(0.023)	(0.024)
R-squared	0.557	0.586	0.658	0.672	0.801	0.854
Observations	82	82	95	95	88	88
	Panel B: Using conventional continent dummies					
Yrs since agr. tran.	0.152^{***}	0.162^{***}	0.063^{***}	0.081^{***}	0.064^{***}	0.068^{***}
	(0.027)	(0.034)	(0.010)	(0.017)	(0.020)	(0.021)
R-squared	0.488	0.515	0.688	0.697	0.844	0.853
Observations	82	82	101	101	89	89
	Panel C: Excluding countries experiencing late transition (within the last 3000 years)					
Yrs since agr. tran.	0.137^{***}	0.138^{***}	0.060^{***}	0.056^{*}	0.088^{***}	0.067^{*}
	(0.037)	(0.047)	(0.019)	(0.032)	(0.031)	(0.038)
R-squared	0.487	0.602	0.627	0.667	0.764	0.826
Observations	67	67	79	79	74	74
Region dummies	Yes	Yes	Yes	Yes	Yes	Yes
Geographic controls	No	Yes	No	Yes	No	Yes

Notes: the dependent variable is the levels of technology adoption in 1000 BC, 1 AD or 1500 AD. The region dummies are Africa, Eurasia, Oceania, North America and South America. The geographic controls are climate, latitude, axis (the orientation of continent), size of landmass, landlocked dummy, island dummy, and terrain ruggedness. An intercept is included in the regressions but is not reported to conserve space. Figures in the parentheses are robust standard errors. ***, ** and * denote significance at the 1, 5 and 10 percent levels, respectively.

Furthermore, the classification of the region dummies used throughout the paper is based on the agricultural spread zones. In other words, countries are grouped based on the relevant spread regions of agriculture that they belong to, which results in the following five macro-regions: Africa, Eurasia, Oceania, North America and South America. The conventional approach, however, is to consider the following five landmasses as continents: Africa, America, Asia, Europe and Oceania. In panel B, we control for the region effects using the conventional classification to check if our results are distorted by this consideration. As is evident, the significance of the parameter estimates of agricultural transition is not driven by how we control for region effects.

Finally, the estimations so far do not distinguish between countries that experienced the transition in the very distant past from those which transit to agriculture more recently. This consideration is relevant since in the event that the significance of agriculture disappears after dropping countries with late transition dates, this would suggest that agricultural transition does not have a long-term effect on comparative technological development. We choose 1000 BC as the cut-off point since this is the date for which data of technology adoptions levels are first available. By including countries that transit to agriculture only after 1000 BC in our previous analyses, we have implicitly embraced the idea that how many more years would be needed to transpire before these countries underwent transition is relevant to determining their technological levels in 1000 BC. This may be a strong assumption. Hence, it is necessary to exclude countries that transit to agriculture after 1000 BC in the estimations to check if our results still prevail. Panel C reports the findings. As is evident, except for the fact that the coefficients of agricultural transition now become statistically significant only at the 10 percent level in two out of six cases, overall, the estimates are largely robust.

4. FURTHER ANALYSES

4.1 Are there persistent effects of technology adoption?

This section analyses whether the effect of technology adoption is persistent, and if so, whether controlling for this persistent effect would render the effect of agricultural transition insignificant. Table 6 reports the findings. First, we include technology adoption in 1 AD in columns (1a) and (1b) (without and with control variables, respectively) to examine whether it has a significant effect on the subsequent adoption level in 1500 AD. Its coefficients are found to be highly significant at the one percent level, suggesting that technology adoption has a persistent effect. This finding is consistent with the results of Comin *et al.* (2010). Interestingly, despite controlling for the initial adoption level of technology, agricultural transition continues to exert a statistically significant influence on technology adoption in 1500 AD.

Table 6: Analyzing the persistent effects of technology adoption

$Dep.\ Var.$ =	(1a)	(1b)	(2a)	(2b)	(3a)	(3b)
$Tech.adop.in\ X$	X = 1500 AD	X = 1500 AD	X = 1500 AD	X = 1500 AD	X = 1 AD	X = 1 AD
$Yrs\ since\ agr.tran.$	0.049**	0.048**	0.098***	0.099**	0.054	0.060
	(0.021)	(0.024)	(0.034)	(0.041)	(0.034)	(0.044)
$[Beta\ coefficients]$	[32.7%]	[32.0%]	[62.0%]	[62.4%]	[39.7%]	[43.7%]
$Tech.adop.in\ 1\ AD$	0.337***	0.316***				
	(0.090)	(0.086)				
$[Beta\ coefficients]$	[31.0%]	[29.0%]				
$Tech.adop.in\ 1000\ BC$			-0.081	-0.048	0.231*	0.237*
			(0.136)	(0.138)	(0.123)	(0.133)
$[Beta\ coefficients]$			[-7.1%]	[-4.2%]	[23.3%]	[23.9%]
R-squared	0.862	0.886	0.817	0.843	0.727	0.727
Observations	87	87	77	77	81	81
Region dummies	Yes	Yes	Yes	Yes	Yes	Yes
Geographic controls	No	Yes	No	Yes	No	Yes

Notes: the dependent variables are the levels of technology adoption in 1500 AD (columns (1) and (2)) and 1 AD (column (3)). The timing of agricultural transition is instrumented by distance to the Neolithic center and biogeography. The region dummies are Africa, Eurasia, Oceania, North America and South America. The geographic controls are climate, latitude, axis (the orientation of continent), size of landmass, landlocked dummy, island dummy, and terrain ruggedness. An intercept is included in the regressions but is not reported to conserve space. Figures in the parentheses are robust standard errors. ***, ** and * denote significance at the 1, 5 and 10 percent levels, respectively.

In columns (2a) and (2b), we repeat this exercise by using technology adoption in 1000 BC as the variable that captures the initial condition. In this case, we do not find any persistent effect of technology while the coefficients of agricultural transition dates remain statistically significant. In columns (3a) and (3b), we examine how the timing of agricultural transition affects technology adoption in 1 AD while controlling for the effect of initial adoption in 1000BC. The evidence suggests a weak persistent effect of technology adoption, and the timing of agricultural transition is not statistically significant. Overall, our results are mixed in terms of whether initial technological development or the timing of agricultural transition matter more for the subsequent adoption levels of technology.

In Table 7, we carry out some mediation analyses to decompose the effect of the timing of agricultural transition while controlling for all geographic and regional effects. Specifically, we use the Sobel test to investigate if the indirect effect of agricultural transition dates on subsequent technology adoption via influencing initial technology adoption is statistically different from zero (see MacKinnon *et al.* (1995) for details). Considering the mediation effect of technology adoption in 1 AD in column (1), the Sobel test statistic is estimated to be 0.018 with a p-value of 0.011. Thus, the null of no mediation is rejected at the 5% level of significance. Moreover, the mediation effect is quite material, with approximately 49.1% of the total effect of agricultural transition timing on technology adoption in 1500 AD being partially mediated by the initial technological development.

Table 7: Analysis of the mediation tests

	(1)	(2)	(3)
$Dep.\ Var. = Tech.adop.in\ X$	X = 1500 AD (the mediation effect of Tech. adop. in 1 AD)	X = 1500 AD (the mediation effect of Tech. adop. in 1000 BC)	X = 1 AD (the mediation effect of Tech. adop. in 1000 BC)
Direct effect	0.018^{*} [p = 0.087]	0.027^{*} [p = 0.052]	0.007 [p = 0.663]
Indirect effect (Sobel test)	0.018^{**} [p = 0.010]	0.015^{*} [p = 0.059]	0.037^{***} [p = 0.001]
Total effect	0.036^{***} [p = 0.002]	0.042^{***} [p = 0.001]	0.044^{***} [p = 0.006]
% of total effect mediated	49.1%	35.6%	83.2%
Observations	87	77	81
Region dummies	Yes	Yes	Yes
Geographic controls	Yes	Yes	Yes

Notes: The Sobel test statistics are calculated using the approach described in MacKinnon (2008). This method tests the null hypothesis that there is no indirect effect from the timing of agricultural transition ($Yrs\ since\ agr.tran.$) via the channels considered ($Tech.adop.in\ 1\ AD$ for column (1) and $Tech.adop.in\ 1000\ BC$ for columns (2) and (3)). The approach involves estimating two regression equations. Take column (1) as an example, first we estimate the parameter (β_1) describing the effect of $Yrs\ since\ agr.tran.$ on the mediator ($Tech.adop.in\ 1\ AD$) (Model 1). Next, the direct effect is estimated by regressing $Tech.adop.in\ 1500\ AD$ on $Yrs\ since\ agr.tran.$ while controlling for the mediator (Model 2). The coefficient of $Yrs\ since\ agr.tran.$ provides the magnitude of this effect (β_2). The indirect effect is given by the product of β_1 and β_3 where β_3 measures the strength of the correlation between $Tech.adop.in\ 1500\ AD$ and $Tech.adop.in\ 1\ AD$ in Model 2. This term also reflects the size of the mediation, which essentially depends upon the extent to which $Yrs\ since\ agr.tran$ influences the mediator (β_1) and the extent to which the mediator affects $Tech.adop.in\ 1500\ AD$ (β_3). ***, ** and * indicate significance at the 1, 5 and 10 percent levels, respectively.

The mediation effect is found to be much weaker in column (2) where the initial condition is measured as of 1000 BC. In this case, approximately 64.4% of the total effect comes directly from the timing of agricultural transition. Consistent with the findings of Table 6, there is clear evidence supporting the notion that the effect of the timing of agricultural transition on technology adoption in 1 AD is significantly mediated by the initial condition of technological development in 1000 BC (column (3)). Overall, the analyses performed in Tables 6 and 7 suggest that the direct role of agricultural transition is more significant for the 1500 AD estimates, but the reverse is found for the 1 AD estimates.

4.2 Controlling for the effects of other early development

While the above results show that technology adoption levels in the pre-modern (up to 1 AD) and early modern period to 1500 AD are critically influenced by the timing of agricultural transition, we cannot rule out the possibility that the effects of a transition that occurred in the very distant past may have evolved into other forms, which continue to exert an influence on technology adoption subsequently. Alternatively, our estimates may be biased due to the failure to account for some omitted channels through which agricultural transition affects technology adoption. For instance, the effect of agricultural transition can potentially affect technology adoption indirectly through influencing other developments. These concerns invite some additional analyses, and the results are presented in Table 8.

First, Diamond's (1997) theory proposes that the Neolithic transition not only precipitated higher adoption levels of technology, but also led to the formation of state polities. The transition to fully-fledged agricultural production gave rise to rapid population growth where more extensive, complex and settled forms of agricultural societies gradually emerged out of the initial hunter-gatherer base. Settled agricultural villages with small-scale political entities governed by supratribal authorities subsequently compounded into larger polities and thereby fully-fledged states emerged (see also Childe, 1950; Ang, 2014). Consistent with this proposition, empirical evidence of Putterman (2008) shows that state history is a significant determinant of economic development in 1500 AD. Accordingly, we control for state antiquity in column (1) using the data of Putterman (2012). If this channel is operative, including a proxy of state history in the estimations may render the effect of agricultural transition insignificant. Despite the fact that state polities were present before 1 AD, we consider state history only from 1 AD to 1500 AD since the data of Putterman (2012) only go back to 1 AD. This should not be a major concern since measuring state history for 1500 years is sufficient to provide an indication of its strength in 1500 AD, assuming that state history prior to 1 AD is relatively unimportant for development in 1500 AD.

Another possible conduit through which agriculture transition affects technology adoption is cultural diffusion barriers. According to the Neolithic demic diffusion model of Ammerman and Cavalli-Sforza (1984), genetic exchange, which reduces cultural barriers to diffusion, is an outcome of agricultural transition. Demic diffusion embodies technology as farmers brought agriculture along with them when they migrated. Increased food production following agricultural settlements led to tremendous increases in population density. Demographic pressures, however, triggered competition for resources, and forced farmers to migrate into other areas with lower population densities. This often caused displacing, replacing or intermixing of populations, and resulted in lower genetic distance between the population of a country and those living at the frontier (Cavalli-Sforza *et al.*, 1996, p. 105). The European migration to North America is a relevant historical example (Cavalli-Sforza, 2000, p. 93). Given that technology adoption may be correlated with diffusion barriers of technology across borders, the causal influence of agricultural transition that we have found so far may disappear once we control for genetic distance to the frontier. We thus also control for genetic distance to the frontier in column (2) to allow for the possibility that it may also have an independent effect on the adoption levels of technology.

Table 8: Controlling for the effects of other early development (IV-2SLS estimates)

	Panel A: 1500 AD estimates							
$Dep.\ Var.$ = $Tech.adop.in\ 1500AD$	(1a)	(1b)	(2a)	(2b)	(3a)	(3b)	(4a)	(4b)
$Yrs\ since\ agr.tran.$	0.061**	0.063**	0.083***	0.088***	0.075***	0.081***	0.069**	0.074**
	(0.024)	(0.027)	(0.021)	(0.027)	(0.022)	(0.027)	(0.027)	(0.031)
$[Beta\ coefficients]$	[40.2%]	[41.7%]	[54.8%]	[58.2%]	[49.4%]	[53.5%]	[45.6%]	[49.0%]
$State\ hist.up\ to\ 1500\ AD$	0.156	0.164*					0.116	0.147
	(0.095)	(0.083)					(0.096)	(0.089)
$[Beta\ coefficients]$	[15.6%]	[8.3%]					[11.7%]	[14.8%]
$Genetic\ distance$			-0.090**	-0.080*			-0.079*	-0.068
$in\ 1500\ AD$			(0.038)	(0.043)			(0.040)	(0.044)
$[Beta\ coefficients]$			[-14.7%]	[-13.0%]			[-12.9%]	[-11.1%]
$Pop\ density\ in\ 1500\ AD$					0.002	-0.001	0.001	-0.001
					(0.002)	(0.002)	(0.002)	(0.002)
$[Beta\ coefficients]$					[5.3%]	[0.4%]	[1.9%]	[3.3%]
R-squared	0.832	0.859	0.806	0.826	0.806	0.826	0.832	0.852
Observations	84	84	84	84	84	84	84	84
	Panel B: 1 AD estimates							
$Dep.\ Var.$ = $Tech.adop.in\ 1AD$	(1a)	(1b)	(2a)	(2b)	(3a)	(3b)	(4a)	(4b)
$Yrs\ since\ agr.tran.$	0.052**	0.054*	0.063***	0.075***	0.057**	0.070**	0.056**	0.060*
	(0.023)	(0.032)	(0.016)	(0.024)	(0.022)	(0.029)	(0.028)	(0.036)
$[Beta\ coefficients]$	[43.3%]	[44.3%]	[52.1%]	[61.9%]	[47.1%]	[57.6%]	[46.3%]	[49.5%]
$State\ hist.in\ 1-50\ AD$	0.067	0.099					0.056	0.072
	(0.093)	(0.106)					(0.090)	(0.103)
$[Beta\ coefficients]$	[7.7%]	[11.5%]					[6.5%]	[8.4%]
$Genetic\ distance$			-0.071	-0.086*			-0.068	-0.080
$in\ 1\ AD$			(0.045)	(0.050)			(0.048)	(0.051)
$[Beta\ coefficients]$			[-13.7%]	[-16.6%]			[-13.2%]	[-15.5%]
$Pop\ density\ in\ 1\ AD$					0.000	0.001	-0.003	0.001
					(0.007)	(0.009)	(0.007)	(0.008)
$[Beta\ coefficients]$					[0.6%]	[1.9%]	[-4.4%]	[0.3%]
R-squared	0.706	0.727	0.703	0.717	0.698	0.709	0.712	0.733
Observations	84	84	84	84	84	84	84	84
	Panel C: 1000 BC estimates							
$Dep.\ Var.$ = $Tech.adop.in\ 1000\ BC$	(1a)	(1b)	(2a)	(2b)	(3a)	(3b)	(4a)	(4b)
$Yrs\ since\ agr.tran.$	0.128***	0.128**	0.134***	0.149***	0.130***	0.140***	0.120***	0.133**
	(0.034)	(0.049)	(0.027)	(0.038)	(0.032)	(0.042)	(0.038)	(0.052)
$[Beta\ coefficients]$	[95.7%]	[95.7%]	[100.2%]	[111.6%]	[96.8%]	[104.4%]	[89.7%]	[99.4%]
$State\ hist.in\ 1-50\ AD$	0.020	0.029					0.058	0.031
	(0.122)	(0.139)					(0.114)	(0.131)
$[Beta\ coefficients]$	[2.4%]	[3.5%]					[7.0%]	[3.8%]
$Genetic\ distance$			0.052	0.049			0.055	0.053
$in\ 1\ AD$			(0.080)	(0.073)			(0.081)	(0.072)
$[Beta\ coefficients]$			[10.2%]	[9.6%]			[10.9%]	[10.5%]
$Pop\ density\ in\ 1\ AD$					-0.003	-0.003	-0.002	-0.002
					(0.010)	(0.012)	(0.010)	(0.012)
$[Beta\ coefficients]$					[-4.0%]	[-4.0%]	[-2.9%]	[-3.5%]
R-squared	0.528	0.557	0.526	0.530	0.527	0.542	0.545	0.556
Observations	71	71	71	71	71	71	71	71
Region dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Geographic controls	No	Yes	No	Yes	No	Yes	No	Yes

Notes: the dependent variables are the levels of technology adoption in 1500 AD (panel A), 1 AD (panel B) and 1000 BC (panel C). The timing of agricultural transition is instrumented by distance to the Neolithic center and biogeography. The region dummies are Africa, Eurasia, Oceania, North America and South America. The geographic controls are climate, latitude, axis (the orientation of continent), size of landmass, landlocked dummy, island dummy, and terrain ruggedness. An intercept is included in the regressions but is not reported to conserve space. Figures in the parentheses are robust standard errors. ***, ** and * denote significance at the 1, 5 and 10 percent levels, respectively.

Barriers to cultural diffusion are captured by the degree of genealogical unrelatedness between two populations using the genetic distance to the global frontier data of Spolaore and Wacziarg (2009). Spolaore and Wacziarg (2009) argue that genetic distance provides a summary measure for the long-run divergence in a number of human traits such as cultures, customs, beliefs, habits, etc., which are transmitted from one generation to another over a long period of time. Such a divergence underlies the existence of some development barriers which prevent the diffusion of innovations from the world technological leader. That is, countries with genetic traits very different from the frontier due to a longer duration of historical non-relatedness face greater barriers to technology adoption. Genetic distance reflects the degree of genealogical dissimilarities or historical unrelatedness between two populations. The data are obtained from Spolaore and Wacziarg (2009). Following their approach, genetic distance from the frontier is defined as the genetic distance for a particular country relative to the technological frontier in 1500 AD. Spolaore and Wacziarg (2009) define England as the global frontier in 1500 AD whereas we choose Italy since it was one of the technologically most sophisticated countries several hundred years before 1500 AD, and England only became a leader circa 1500 AD.

The above discussions also suggest that agricultural transition can affect technological development through affecting its effect on population density. To control for the effect of demographic pressure, we therefore also include population density in 1500 AD in column (3) separately and jointly with state history and genetic distance to the world technological frontier in column (4).

Considering first the results with the inclusion control variables for 1500 AD (panel A, all columns (b)). The results in columns (1b) and (2b) of panel A, respectively, show that while the coefficients of state history and cultural diffusion barriers are statistically significant and have the expected signs, their effects are only significant at the 10 percent level. When population density is added to column (3b), the coefficient of agricultural transition is still statistically significant at the one percent level, but the effect of population density is insignificant.[1] When

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[1] When population density is regressed on agricultural transition, where the latter is instrumented by distance to the Neolithic core and biogeography, parameter estimates of agricultural transition are not precisely estimated at any

these three additional early development measures are jointly included in column (4b), only the coefficient of agricultural transition is found to be statistically significant. The beta coefficients reported in all columns suggest that variations in the timing of agricultural transition has a much larger economic effect than all other indicators of early development, and hence is much more powerful in explaining the variation in technology adoption levels in 1500 AD across countries. The results are similar when control variables are excluded (all columns (a) in panel A). Taken together, the results here suggest that the effect of early agrarian development on technology adoption in 1500 AD is unlikely to work through state history, genetic mix or population density.

A similar exercise, however, cannot be readily performed for the estimates of 1000 BC and 1 AD since, except for population density for the 1 AD estimates, data on their state history, population composition and population levels are not currently available. However, when we repeat the regressions in panel A using some indirect measures (i.e., population density in 1 AD, state presence in 1-50 AD, and genetic distance to Italy mapped by population composition in 1500 AD), the estimates for 1 AD (panel B) and 1000 BC (panel C) are not overturned. Except for the coefficient of genetic distance in the estimates of 1 AD (panel B, column (2b)), which is statistically significant only at the 10 percent level, coefficients of all additional early development indicators are not precisely estimated. The coefficients of agricultural transition, however, are found to be statistically and economically significant in all cases. Under the assumption that state presence in 1-50 AD and population density in 1 AD were similar to what they were 1000 years ago, and population mixes were largely similar in 1500 AD, 1 AD and 1000 BC, these results imply that an early exposure to agriculture induces an early head start in technological development in 1000 BC and 1 AD, and this effect does not work through the channels considered above. These analyses are, of course, crude and caution should be exercised when interpreting the results.

Summing up, the results in this subsection suggest that agricultural transition directly matters for an early start in technological development. The mediation analyses reports in Table 9 are consistent with the above findings in the sense that the mediation effects of genetic distance and population density are rather weak. The evidence, however, suggests that the effect of agricultural transition on technology adoption since pre-modern times is significantly mediated by state antiquity, although the impact of state antiquity is found to be negligible in Table 8. Overall, the results here are still largely consistent with the above findings that the

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conventional levels of significance in all cases. Hence, the results consistently suggest that agricultural transition directly affects technology adoption, independent of its effect on population density.

timing of agricultural transition has a significant direct impact on technology adoption, and such a relationship holds even if we control for other effects of early development.

Table 9: Mediation analyses for the effect of other early development

	(1)	(2)	(3)
	The mediation effect of $State\ hist.$	The mediation effect of $Cultural\ diffusion\ barriers$	The mediation effect of $Pop. density$
	Panel A: 1500 AD estimates		
Indirect effect (Sobel test)	0.019^{***} [p = 0.008]	-0.002 [p = 0.366]	0.001 [p = 0.570]
% of total effect mediated	54.3%	7.2%	3.9%
Observations	84	84	84
	Panel B: 1 AD estimates		
Indirect effect (Sobel test)	0.020^{**} [p = 0.040]	-0.001 [p = 0.986]	0.007 [p = 0.347]
% of total effect mediated	41.5%	0.1%	13.9%
Observations	84	84	84
	Panel C: 1000 BC estimates		
Indirect effect (Sobel test)	0.021 [p = 0.148]	0.001 [p = 0.641]	0.007 [p = 0.495]
% of total effect mediated	21.8%	1.4%	7.6%
Observations	71	71	71
Region dummies	Yes	Yes	Yes
Geographic controls	Yes	Yes	Yes

Notes: The Sobel test statistics are calculated using the approach described in MacKinnon (2008). This method tests the null hypothesis that there is no indirect effect from the timing of agricultural transition ($Yrs\ since\ agr. tran.$) via the channels considered ($State\ hist.$, $Cultural\ diffusion\ barriers$ or $Pop\ density$). The approach involves estimating two regression equations. Take column (1) as an example, first we estimate the parameter (β_1) describing the effect of $Yrs\ since\ agr. tran.$ on the mediator ($State\ hist.$) (Model 1). Next, the direct effect is estimated by regressing $Tech. adop.$ on $Yrs\ since\ agr. tran.$ while controlling for the mediator (Model 2). The coefficient of $Yrs\ since\ agr. tran.$ provides the magnitude of this effect (β_2). The indirect effect is given by the product of β_1 and β_3 where β_3 measures the strength of the correlation between $Tech. adop.$ and $State\ hist.$ in Model 2. This term also reflects the size of the mediation, which essentially depends upon the extent to which $Yrs\ since\ agr. tran$ influences the mediator (β_1) and the extent to which the mediator affects $Tech. adop. in$ 1500 AD (β_3). *** and ** indicate significance at the 1 and 5 percent levels, respectively.

4.3 How agricultural transition affects technology adoption in each sector

The data of Comin *et al.* (2010) are available at the sectoral level, which enables us to investigate how technology adoption levels in each sector respond to the transition to agriculture. Thus, to gain some insight into how the effect of agricultural transition works through technology adoption, we replace the dependent variables at each time period using the sectoral estimates of technology adoption.

Table 10: Effects of agricultural transition on adoption in each sector (IV-2SLS estimates)

Dep. Var. = *Tech. adop. in sector Y*	(1)	(2)	(3)	(4)	(5)
	Y = Agriculture	Y = Communication	Y = Transport	Y = Industry	Y = Military
	Panel A: Technology adoption in 1000 BC				
Yrs since agr. tran.	0.205^{***}	0.139^{***}	0.193^{***}	0.113^{**}	0.099^{***}
	(0.074)	(0.042)	(0.041)	(0.046)	(0.034)
R-squared	0.208	0.379	0.582	0.643	0.625
Observations	82	82	82	82	82
	Panel B: Technology adoption in 1 AD				
Yrs since agr. tran.	0.093^{**}	0.171^{***}	0.137^{***}	0.045^{**}	0.045^{**}
	(0.036)	(0.058)	(0.039)	(0.021)	(0.021)
R-squared	0.287	0.325	0.530	0.578	0.578
Observations	95	95	95	95	95
	Panel C: Technology adoption in 1500 AD				
Yrs since agr. tran.	0.081^{**}	0.115^{***}	0.053^{***}	0.045^{*}	0.094^{**}
	(0.032)	(0.038)	(0.019)	(0.025)	(0.040)
R-squared	0.593	0.671	0.795	0.916	0.702
Observations	88	88	88	88	88
Region dummies	Yes	Yes	Yes	Yes	Yes
Geographic controls	Yes	Yes	Yes	Yes	Yes

Notes: the dependent variable is the adoption levels of technology in sector Y for 1000 BC, 1 AD or 1500 AD, where Y = agriculture, communication, transport, industry or military. The timing of agricultural transition is instrumented by distance to the Neolithic center and biogeography. The region dummies are Africa, Eurasia, Oceania, North America and South America. The geographic controls are climate, latitude, axis (the orientation of continent), size of landmass, landlocked dummy, island dummy, and terrain ruggedness. An intercept is included in the regressions but is not reported to conserve space. Figures in the parentheses are robust standard errors. ***, ** and * denote significance at the 1, 5 and 10 percent levels, respectively.

The results reported in Table 10 show that the effect of agricultural transition on technology adoption works through all sectors in 1000 BC, with agriculture, communication and transport being the sectors that benefit most from an early exposure to agriculture. Similar results are obtained for the estimates in 1 AD. That an earlier transition to agriculture induces a high level of agricultural technology adoption is not surprising. The importance of agricultural transition for technological development in the other two sectors during the pre-modern period perhaps reflect the fact that the development and adoption of communication and transport technologies benefit most from the domestication of pack and draft animals following the transition to agriculture, which facilitated the spread of writing and records, along with breeding and husbandry techniques. In the case of 1500 AD, the results are also similar, except for the finding that the effect of agricultural transition on the military sector is more significant than that on agriculture and transport. The estimates without control variables are largely similar and hence are not reported to conserve space.

5. CONCLUSIONS

While significant progress has been made in improving our understanding of the role of agricultural transition in explaining variations in income across countries, the way that early technology adoption reacts to historical agrarian development is still not known. The central theme of this paper is that an early transition to sedentary agriculture provides a developmental head start, which enables a country to adopt technologies in its early stages of development.

This premise is built on the influential hypothesis of Diamond (1997) that countries which made the transition to agriculture earlier are able to maintain their lead and continue to enjoy a higher level of technological development than others. The underlying premise of this hypothesis is that technological progress has continued to build upon the foundations laid down during the transition, through an endogenous process of knowledge creation. Differences in the stock of technology accumulated over the course of economic development give rise to differentials in the costs of its adoption which explain variations in the levels of technological development.

Potential endogeneity, spurious regressions and specification problems are dealt with using geographic distance to the Neolithic center and an index of biogeographic endowments as instruments for the timing of agricultural transition. Exploiting the exogenous sources of cross-country variations in the dates of agricultural transition based on this identification strategy, the analysis demonstrates that the locations in which agrarian innovations first took place, by way of an earlier transition to agriculture, have a far reaching positive influence on the subsequent levels of technological development in 1000 BC and, to a lesser extent, 1 AD and 1500 AD. Thus, our results lend credence to the influential Diamond hypothesis.

Further investigations were conducted to uncover the mechanisms through which agricultural transition affects technology adoption levels. In particular, we find that the significance of the timing of agricultural transition does not disappear even after controlling for the effects of state history, cultural diffusion barriers and population density. These results imply that an early exposure to agriculture directly enhances technology adoption during the ancient, pre-modern and early modern periods. This effect does not work through either facilitating the establishment of social structures, small polities and early political institutions, increasing the intensity of population admixing or expanding the density of populations. However, these findings could be driven by the fact that the channel indicators considered here are measured with errors or early agriculture affects subsequent technological development via other channels.

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APPENDIX

Table A1: Definition of variables and data sources

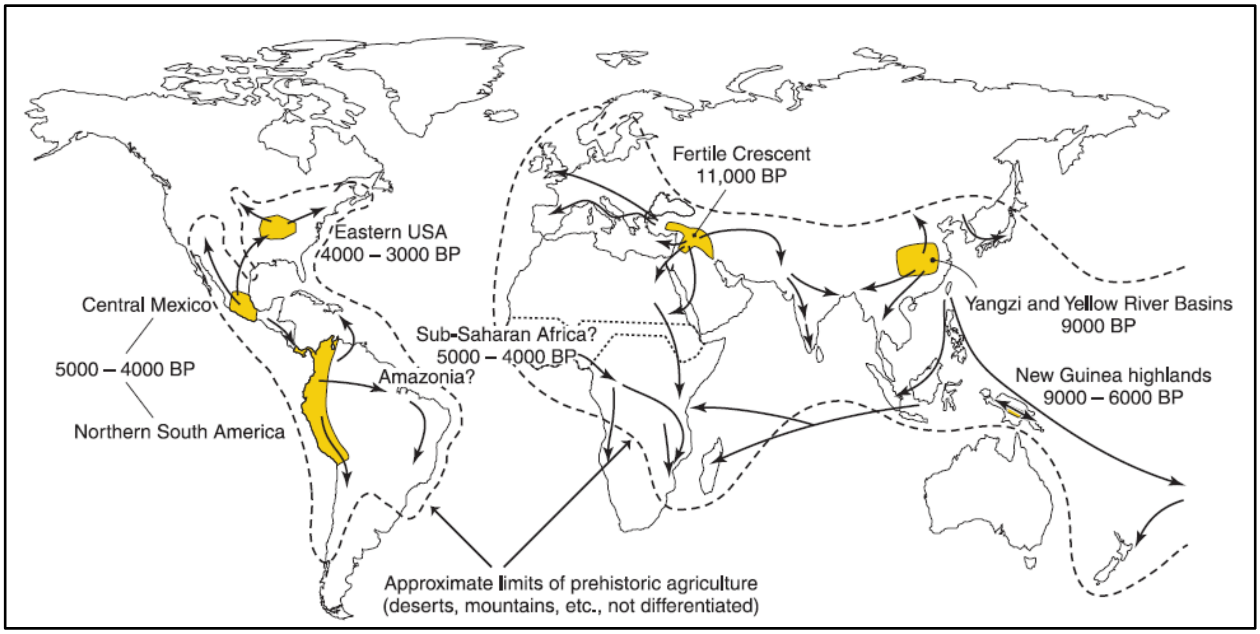
Variable	Description	Source
Technology adoption	The average adoption levels of technology in 1000 BC, 1 AD and 1500 AD. It covers the following sectors: agriculture, transportation, communications, industry and military.	Comin *et al.* (2010)
Years since agricultural transition	The number of years elapsed, in 2000 AD, since the transition to agriculture was estimated to occur (in thousand years).	Putterman (2006)
Neolithic distance to the regional center	This measure captures the geographic distance between a country and its nearest Neolithic center in the same agricultural spread zone. The Neolithic points of origins are chosen based on the estimated archaeological sites for the centers of origin of agriculture reported in Diamond (1997), Diamond and Bellwood (2003) and Bellwood (2005). Geographical distance is calculated using the 'Haversine' formula, which calculates the shortest distance between two points on the surface of a sphere based on their longitudes and latitudes. See section 2.3 for details.	Diamond (1997), Diamond and Bellwood (2003), Bellwood (2005) and author's own calculation.
Biogeographic endowments	The first principal component of the standardized numbers of domesticable wild plants and animals.	Hibbs and Olsson (2004); Olsson and Hibbs (2005)
Climate	Climate classification of 1 to 4 based on the Köppen's approach. A higher value indicates more favorable climate conditions for agriculture.	Hibbs and Olsson (2004); Olsson and Hibbs (2005)
Axis	The East-West orientation of the axis, calculated as the longitudinal distance between the furthest eastern and western points in each continent divided by latitudinal distance. Unlike Hibbs and Olsson (2004) and Olsson and Hibbs (2005) who use the axis values of the nearest continents for some island countries, we directly measure the axes for these countries.	Hibbs and Olsson (2004); Olsson and Hibbs (2005) and author's own estimation using the horizontal width and vertical length data from http://www.worldatlas.com/
Landmass size	Size of landmass to which a country belongs (in millions of square kilo meters)	Olsson and Hibbs (2005)
Latitude	Absolute value of the latitude of each country.	CIA World Fact Book
Landlocked	A dummy variable that equals 1 if a country is fully enclosed by land and 0 otherwise.	CIA World Fact Book
Island	A dummy variable that equals 1 if a country is an island and 0 otherwise.	CIA World Fact Book
Terrain ruggedness	An index that quantifies small-scale terrain irregularities in each country.	Nunn and Puga (2012)
State antiquity	An index of state history covering the period from 1 AD to 1500 AD, scaled to take values between 0 and 1. The dataset was originally introduced by Bockstette *et al.* (2002), but the current paper uses its latest version, v3.1.	Putterman (2012)
Genetic distance to the technology frontier	The degree of genealogical similarities or historical relatedness for the population of a particular country relative to that of the technological frontier up to 1500 AD, i.e., Italy. Data on population are matched to countries based on their ethnic composition as of 1500 AD.	Spolaore and Wacziarg (2009)
Population density	The population divided by land area.	McEvedy and Jones (1978) and World Development Indicators (2012).

Table A2: Estimated archaeological sites of the centers of agricultural origin for each region and the modern-day countries with significant territory within the sites

Region / Country	Neolithic Center (date of farming spread)	Present-day country
North America	Central Mexico (5,000-4,000 BP)	Mexico
South America	Northern South America (5,000-4,000 BP)	Colombia, Ecuador, Peru and Panama
Sub-Saharan Africa	West Africa, the Sahel and Ethiopian highland (5,000-4,000 BP)	Cote D'Ivoire, Ethiopia and Ghana
Middle East & North Africa	Fertile Crescent (11,000 BP)	Iraq, Syria and Turkey
South Asia	Fertile Crescent (11,000 BP)	Iraq, Syria and Turkey
Europe & Central Asia	Fertile Crescent (11,000 BP)	Iraq, Syria and Turkey
East Asia	Yangzi and Yellow River Basins (9,000 BP)	China
Oceania (excluding PNG)	Yangzi and Yellow River Basins (9,000 BP)	China
Papua New Guinea (PNG)	New Guinea Highlands (9,000-6,000 BP)	Papua New Guinea

Notes: the Neolithic sites and the years during which farming was spread are taken from the estimates of Diamond (1997), Diamond and Bellwood (2003) and Bellwood (2005). The present-day countries are chosen by the author.

Figure A1: Map of agricultural homelands and spread of Neolithic farming techniques



Source: Diamond and Bellwood (2003).