Population Growth and Technological Change: One Million B.C. to 1990

by Michael Kremer

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Research Digest by Matt Clancy

Theoretical contribution

This paper establishes a simple model of global population and technological innovation, and then demonstrates that the model is consistent with some long-run facts about the history of humanity. The model is based on three core ideas.

First is the notion that any given person having an idea for a new technology is basically down to luck. Maybe the randomness is in their genes and upbringing; they were lucky to be born a genius. Or maybe the randomness is in the circumstances that spark an idea; they were lucky to be in the right place at the right time. The upshot is that more people means more chances of having new ideas, just like more lottery tickets means a higher probability of winning the jackpot.

Second is the notion that the level of technology helps determine living standards. Holding the population constant, a higher level of technology means higher living standards.

Third is the notion that populations grow when living standards are above a threshold and shrink below it. We can imagine this threshold is the human biological subsistence level; below a certain level of living standards, people starve. But it doesn't need to be due to biological needs, for the model to work it just needs to be that the population grows when living standards are higher and shrink when very low.

Kremer combines these three ideas in a set of increasingly sophisticated models. For the purposes of this digest, I'll present a version of the model that is even simpler than the simplest model Kremer presents, but it suffices to illustrate the intuition of the model.

To capture the notion that more people means more new ideas, first define a few variables. Let the level of technology in the economy be represented by A and the annual growth rate of technology be represented by a. The size of the population is P. Now suppose the number of new ideas in a year is proportional to the population as follows:

$$a = GP \tag{1}$$

Where G is the proportion of people that have an idea that raises A by 1%. For now, just assume G is constant across all time.

Next, to capture the notion that the level of technology determines living standards, make the unrealistic assumption that only two factors determine the size of the economic pie: technology (represented by A) and land (represented by T). The size of the economy is obtained by multiplying these together: AT. This economic pie is evenly divided among the population P to determine income per person (represented by Y):

$$Y = \frac{AT}{P} \tag{2}$$

The preceding is very unrealistic, because in reality people work and grow the economic pie as well as consume it. This is an area where I've simplified the model Kremer presents. In the paper, the size of the economic pie is also a function of labor. The important point is that the increase in the size of the economic pie when you add labor is not enough to raise living standards: if you double the population, living standards don't get cut in half (because more workers means more stuff is produced), but it does fall. Nonetheless, the assumption above makes it possible to illustrate the model's intuition without derivatives.

Finally, to capture the idea that the population grows when income is above a threshold and shrinks below it, define $\bar{Y}$. This is a tipping point for income; whenever income per person is above $\bar{Y}$ the population increases, and whenever income per person is below $\bar{Y}$ the population shrinks.

Combine this threshold effect with equation (2) and we can see that in the long-run, the following condition always holds:

$$\bar{Y} = \frac{AT}{P} \tag{3}$$

(the only difference from equation (2) is the Y has been replaced by $\bar{Y}$). If income per person ever rises above $\bar{Y}$, the population P grows. But since the size of the economic pie is fixed and we're dividing it between more people, this leads to a reduction in living standards Y until they reach $\bar{Y}$. At that point, the growth rate of the population (P) stops and the population stabilizes. Conversely, if income per person ever falls below $\bar{Y}$, the population (P) shrinks and the economic pie is divided among fewer people. This leads to an increase in living standards Y until they reach $\bar{Y}$. Again, at that point the population stops growing and stabilizes. So in the long run, the equation (3) always holds.

We can rearrange equation (3) to find the long-run population level:

$$P = \frac{AT}{\bar{Y}} \tag{4}$$

Equation (4) says the population is determined by the level of technology, the amount of land T, and the fixed income level for a stable population $\bar{Y}$. Of these, only the technology level (A) can change, since land is fixed (we're assuming this is a model of the entire earth) and the threshold income $\bar{Y}$ is fixed. Let p represent the annual growth rate of the population. It turn out:

$$p = a \tag{5}$$

In other words, the growth rate of the population is identical to the growth rate of technology, given equation (4), since A is the only thing that can change. In other words, if the level of technology grows by 5%, the population grows by 5%.

But our first equation asserted that $a = GP$. If we substitute this for a in equation (5) we obtain:

$$p = GP \tag{6}$$

Equation (6) makes a surprising assertion about the growth rate of the global human population. When we think of non-human populations, as long as resources are abundant, the population grows at a constant exponential rate (for example, doubling in size every year). But equation (6) asserts the growth *rate* of the global human population is proportional to the *size* of the population. Small populations grow at slow rates, big populations grow at faster rates. This is faster than exponential growth!

The key difference between humans and non-humans, in this model, is that for humans a bigger population leads to faster technological progress. This leads to an economy that grows more quickly. And a bigger economy can support a bigger population. This in turn supports even faster technological progress, in a virtuous circle of ever accelerating population growth and technological progress.

The rest of Kremer's paper establishes that this basic intuition will hold even as you impose more and more realistic assumptions on the model.

First, let's take a closer look at equation (2) which determines the size of the economy. In reality, the economy's size is determined by more than just technology and land. As already noted, his model includes labor as another factor that determines the size of the economy. But he also shows his model works when you add capital as an additional factor of production.

Second, let's turn to equation (1), which asserts the growth rate of technology is a constant fraction of the population. We can quibble with this assumption in at least three ways. First, maybe the share of the population that comes up with new ideas is increasing in living standards (Y). Maybe you need to have some distance from the struggle for survival before you have time and mental energy to indulge in invention and discovery. So Kremer investigates a version of his model where richer societies have a higher G than poorer ones, but his results are not changed, basically because most societies end up with the same living standards in the long run anyway.

Alternatively, maybe the rate at which you come up with new ideas is itself related to the technology level A. We can suppose, for example, that access to technologies like a printing press or computer makes it more likely any given person will come up with a new idea. In that case, the growth rate of technology (a) should be increasing in the level of technology A, as well as the population P. On the other hand, maybe it gets harder to come up with new ideas as the technology level improves, because the easiest ideas are invented first. It would seem easier to invent the wheel than the iPhone, for example. But Kremer shows this also does not affect the main conclusion.

Or maybe the fraction of people who come up with new ideas is related to the size of the population P. For example, if you have enough people, maybe some can specialize in production and others in coming up with ideas. Or maybe having lots of people to talk with or bounce ideas off makes more likely you'll have a good idea. As long as G is increasing with P though, then the effect would actually accelerate the trend we've already observed, because bigger populations would have an even higher share of people come up with ideas.

Third, Kremer checks to see how well his theory holds up when he modifies his assumptions about how populations grow. For example, maybe population growth slows down above a certain income level: this certainly seems to be the case in the real world. That has the effect of slowing down the runaway cycle where more people leads to more ideas, which leads to more people, and so on. But as long as the global population continues to grow, his results hold up.

Empirical Contributions

Kremer conducts two simple tests of this theory. The first relies on equation (6) and predicts that bigger populations should have a faster population growth rate. Kremer assembles 37 measurements of the Earth's population ranging, as promised, from 1,000,000 B.C.E. to 1990 A.C.E. He uses these to compute growth rates for the global population and then tests for a positive relationship between population size and subsequent growth rate. Figure 1 plots his data. As is obvious from the figure, he finds a robust and strong relationship: on average, when the global population is larger, it grows at a faster rate in the subsequent decades and centuries.

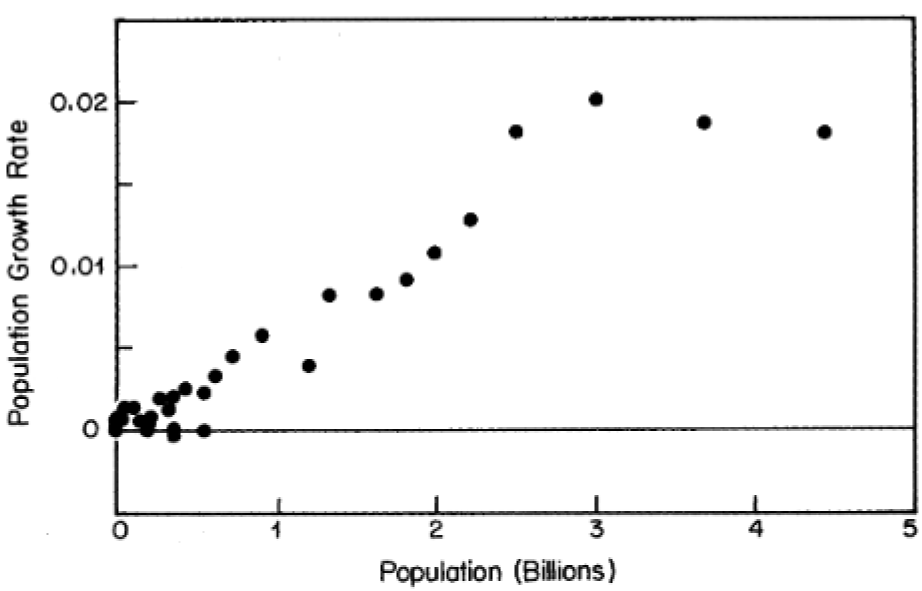

FIGURE I
Population Growth Versus Population

Second, Kremer leverages equation (4), which relates the size of a population to the state of technology, land, and threshold income. He asks us to suppose that during humanity's pre-history, we all had access to the same basic suite of technologies, which broadly diffused to all people across the globe (think things like fire, spears, and so on). Then, in 10,000 B.C.E. the ice age ended with the melting of the polar ice caps. The subsequent rise in sea levels split the Earth into five landmasses with no means of contact between them until the invention of seafaring ships many millennia later. The biggest of these landmasses was Europe/Asia/Africa. The next largest was North and South America (connected to Asia via the Bering land bridge before the rising sea levels). The third largest was Australia, followed by Tasmania, and the smallest was tiny Flinders island.

Prior to the severing of their landbridges, these four areas might plausibly have had the same shared level of technology (A), but the human population they can support varies with the size of land. Kremer asks us to imagine these five areas developed in isolation from each other until roughly 1500 when seafaring Europeans made contact with them. If Kremer's model is right, the bigger land areas should support more people, which will lead to more ideas, and therefore to a higher population growth rate. When isolation ends in 1500, those that began with more land and a bigger population should have reached a higher technology level, supporting a higher population density than those that began with a small land area and small population. And indeed, we do, as indicated in Table 1.

POPULATION AND POPULATION DENSITY, C. 1500

	Land area (million km^2)	Population c. 1500 (millions)	Population/(km^2)
Old World[a]	83.98	407	4.85
Americas[b]	38.43	14	0.36
Australia[c]	7.69	0.2	0.026
Tasmania	0.068	0.0012–0.005	0.018–0.074
Flinders Island	0.0068	0.0	0.0

a. Sub-Saharan Africa is included in the old world, since there was some contact across the Sahara.
b. There are a wide range of population estimates for the Americas and Australia at the time of European arrival, and McEvedy and Jones's are at the low end. However, higher estimates would not affect the rank ordering.
c. Estimates for Tasmania are based on the *Encyclopaedia Brittanica*.

Table 1

Discussion

Lurking in the background of this paper is a debate among economists about the "scale effect." In models of economic growth, a typical (but not universal) result that falls out of the models is that big economies should grow faster than small ones. This is sometimes viewed as an inconvenient result, because it's not supported by casual observation. For example, in Figure 2, I plot national population in 1950 over the growth of real GDP per capita between 1950 and 2015. Big countries grew a bit faster than small ones, but it's not super compelling.

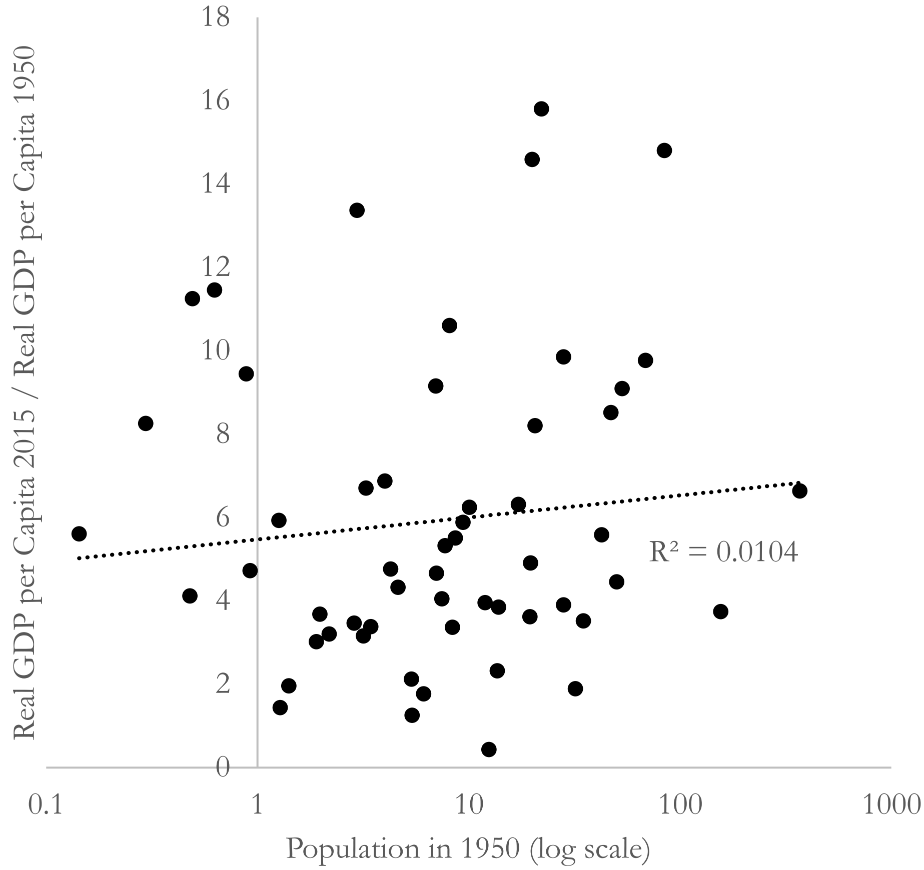

Figure 2. Population and Real GDP per Capita Growth

Kremer's paper suggests that there is something to the scale effect when viewed correctly as a global and long-run trend. It also highlights a few reasons why we shouldn't expect a very strong relationship between real GDP per capita growth and population at the sub-global level. First, a higher level of technology can induce a change in population that reduces living standards. Indeed, in his simple model, living standards are always the same for big or small populations. This is why he focuses on the population growth rate in his empirical tests, not on some measure of living standards.

Second, because ideas do not respect borders, we should not expect a strong relationship between population size and growth unless the populations are isolated from each other. Implicitly, Kremer is assuming other factors outside his model can help explain how ideas are implemented or not in different regions of the world. For example, maybe there was something about Britain in the 1700s that allowed it to pull together ideas from all over the world and become the seat of the industrial revolution, despite the small size of its population. Whatever these outside factors are, if they are not correlated with population, then we shouldn't expect a strong correlation between national population and growth.

Third, in Kremer's more sophisticated models, the share of the population that can come up with ideas can be related to living standards (which can also vary in his more sophisticated models).

This may mean that a small rich country might be able to mobilize more of its population for innovation, compared to a large poor country.

A second important trend not explained well by Kremer's model is the dramatic slowdown in the population growth rate in the last century. This is visible as the sharp trend break in Figure 1, where population growth rate levels off around a global population of 3 billion. Kremer's model can accommodate this kind of demographic transition by assuming the population growth rate is related to living standards and slows down above a certain level. But such a trend break does not emerge from any assumptions about the relationship between population and technology and complicates the otherwise simple relationship between population size and growth rate.

Kremer briefly considers a policy implication of his model: can we advance technology more quickly by encouraging people to have more children? It turns out the answer is yes, at least in the long run! That said, there are at least three caveats. First, the short-run effect of a higher population might be negative if it reduces living standards enough to reduce the share of the population that comes up with ideas. But in the long run, this effect will wash out. Second, because ideas don't respect national borders, it might not be in the national interests of a country to pursue such a policy, since the reduction in living standards would be born entirely by the nation but the benefits of more ideas would flow to other nations as well. Third, Kremer's model assumes new ideas can be discovered without end. If it turns out that there is a limit to what can be known and invented, then at some point more people may not mean more ideas.

Data

Kremer's paper relies on a small number of estimates of global and regional population. He relies on UN data for population from 1920 onward and McEvedy and Jones (1978) for estimates from 10,000 B.C.E. to 1900. These, in turn, are compiled by adding up regional population estimates that usually trace their source to historical censuses (e.g., by ancient Rome or China), or are based on archaeological and anthropological evidence. Population estimates before 10,000 B.C.E. are based on Deevey (1960). Results are robust to using alternative (but older) estimates of global population.

Methods

Kremer's main empirical tests rely on ordinary-least-squares regressions of the following core equation:

$$\text{Population Growth Rate}_t = \alpha + \beta \times \text{Population}_{t-1} + \varepsilon_t \tag{7}$$

with various checks for robustness to heteroscedasticity in the error terms, unit roots, and trend breaks.