War and genocide: is there a connection to transitions from stagnation to growth? (preliminary)

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Abstract: The 20th century saw rising levels of per-capita incomes worldwide, but also phases of enormous human killings. The number of people killed annually in war and genocide across the world increased up until the mid 20th century and has since then been declining. Here a growth model is set up to explain these joint trends in killings and economic development. Agents compete for food for their survival. In environments with scarce resources – meaning high population density, and/or low levels of technology – agents allocate more of their time to fight over resources, which can result in war and killings. Technological progress exerts two opposing effects. On the one hand, it mitigates resource scarcity, making conflict less likely; on the other, if war breaks out, it is deadlier if technologies are more advanced. An economy can transit onto a path of peaceful prosperity, but in the transition it may pass a phase of excessive killing, as rising living standards have not yet made war an impossible (or improbable) event, but rising levels of technology have made war extremely lethal if and when it breaks out. Quantitative analysis verifies that the model generates an inversely U-shaped time trend in war and genocide deaths, simultaneously with a take-off from stagnation to growth. The underlying mechanisms are consistent with several stylized facts of growth and conflict, in particular from European history.

1 Introduction

"We need land on this earth...We must continue to receive what is necessary from future apportionments until such time as we are satiated to approximately the same degree as our neighbors."

German industrialist Walter Rathenau in 1913 (as cited by Hardach 1977, p. 8)

This paper tries to formulate a growth theory which can explain a transition from Malthusian stagnation to modern growth, together with certain time trends in war and genocide occurring in this process. Figure 1a shows annualized killings from war and genocide 1900-1987, based on 218 events listed by Rummel (1997, Table 16.A).[1] As seen, whereas the world as a whole grew richer over the 20th century, annual killing rates increased over roughly the first half of the century, and thereafter declined more or less monotonically. This holds both for the total body count, and when dividing by world population.[2]

Figure 1b shows the time paths for war and genocide separately. These move largely in tandem, and the correlation coefficient is 0.77. In that sense, one may think of war and genocide as the same macro phenomenon.

It is also seen in Figure 1b that the trend for the world aggregate is driven by events occurring (or originating) in four world regions: Germany, Japan, (Soviet) Russia, and China. These events were the two world wars, the Holocaust, and communist rule in Russia and China. Germany and Japan became peaceful by 1945, Russia and China somewhat later. However, all show a similar rise-and-fall pattern as the world as a whole (Figure 1c).

[1]The deaths reported in Figure 1a refer to both war and genocide. These time series are highly correlated in Rummel's data: genocides tend to be committed in times of war. The number of people killed annually in each war/genocide is assumed to be uniformly distributed from the first to the last year in which it took place, as reported by Rummel. In many cases the total number of victims of a genocide is not well established, in which case the midpoints of the upper and lower bounds reported by Rummel.

[2]Although the timing differs, the general pattern in Figure 1a is consistent also with other sources and ways to measure the costs and intensities of war. For example, Marshall and Gurr (2005) find that the total number of wars fought worldwide peaked in the 1980's.

Figure 1c also shows per-capita income levels for the same four regions. Despite differences in many details, all four passed a phase of excessive killings in a process of "modernization" – a transition from Malthusian stagnation to sustained growth in per-capita incomes. In China and Russia early economic development brought with it revolution, civil war, and genocide; Germany and Japan saw the rise of racist ideologies, attempted territorial conquests, and genocide. How, then, could a transition from stagnation to growth result in (or arrive at the same time as) such violent events?

The starting point of the theory proposed here is that wars (and by extension genocide, since genocide tends to be perpetrated in times of war) are ultimately generated by competition for land and other scarce resources. This force could, however, express itself through many different proximate channels. For example, conflicts could arise between different groups or classes within one country (as in China and Russia), or between different countries (as the wars fought by Germany and Japan; cf. Walter Rathenau's words above).

The first basic setting considered here treats war as a random event, the probability of which is higher when resource competition is intense. Technological progress mitigates resource scarcity. This reduces competition and the risk of war, but also makes warfare more lethal if it breaks out. A phase of peace may generate growth in population and technology, whereafter an outburst of war (if and when it occurs) is all the more deadly. The simulated time paths for killings and per-capita income resemble those in Figure 1a. The random nature of the transition also seems plausible from a historical perspective: peace must thus prevail for long enough so that technological progress can make resource scarcity, and thus the risk of war, vanish completely; only then can the economy break out of Malthusian stagnation.

As an extension of this basic framework, we then consider a richer model where two countries may choose to fight wars over a territory. Also, agents' choices of fertility, and education of children, are endogenized. This model is more complex but can replicate the same type of patterns shown in Figures 1a-c.

The rest of this paper continues in Section 2 by relating it to earlier literature. Thereafter Section 3 relates the workings of the model to a number of facts about war, conflict, and genocide in human history, in particular Europe over the 19th and 20th centuries. Section 4 sets up a model where war is a random event: it breaks out due to an exogenous shock, but the probability of such a shock depends on the intensity of resource competition, which evolves endogenously over time. Next, Section 5 considers a setting where two countries contest a fixed amount of land and war is modelled as an explicit choice made by the governments of the two countries. Finally, Section 6 ends with a concluding discussion.

2 Existing literature

Most economists interested in theories of conflict have taken a microeconomic approach. They try to explain, for instance, the origin of property rights as a means to avoid conflict when agents weigh the option of appropriation (stealing) against production. (See e.g. Grossman 1991; Grossman and Kim 1995; Hirschleifer 1988, 2001.) However, none of these papers applies the results to issues like, for instance, why 20th century Europe was so war torn, or the trends in worldwide killings shown in Figures 1a-c.

Neither does this literature actually model any link from resource scarcity to violence. An important exception to this, however, is Grossman and Mendoza (2003) who set up a model where competition for resources is induced by a desire for survival, because more consumption means higher probability of survival. Grossman and Mendoza show that if the elasticity of the survival function with respect to consumption is decreasing in consumption, scarcer resources leads to more violence. The survival function used here takes a parametric form which satisfies this Grossman-Mendoza condition.

There is also an empirical literature looking at war and violence within and across countries. See e.g. Collier and Hoeffler (1998, 2004) and many other papers by the same authors. Different from the present study, these do not set up a unified growth model explaining the trends in worldwide killings shown in Figures 1a-c.

Johnson et al. (2005) document that the death toll in many insurgencies (in e.g. Iraq and Colombia) tend to follow a power-law distribution. They also explain this pattern in a model where insurgent units join forces with bigger groups, or break up into smaller. The approach taken here differs by focusing on longer-term time trends in war and genocide, and by linking these trends to growth in population and living standards.

There is also a recent trend in the growth literature trying to explain growth in population and per-capita income, not only over the last couple of decades, but several thousand years back in time. See, among others, Cervellati and Sunde (2005), Galor and Moav (2002), Galor and Weil (2000), Hansen and Prescott (2002), Jones (2001), Lagerlöf (2003a,b), Lucas (2002), and Tamura (1996, 2002). But, again, these do not model war or resource scarcity.

One growth model with endogenous evolution of population and a renewable resource stock is set up by Brander and Taylor (1998), who use the downfall of the ancient civilization on Easter Island as an illustration. However, they do not model violence or conflicts over resources per se, or transitions from Malthusian resource competition to sustained and peaceful growth.

Outside the field of economics there is some work pointing to related mechanisms as those modelled here. Fukuyama and Samin (2002) suggest that Communism and Nazism arose in response to rapid social change and urbanization. These "isms" were also forces of "creative destruction" in the sense that they got rid of pre-modern, rural institutions and social structures in Germany and Russia which hindered economic growth. Today, Al Qaeda may play a related role in the Middle East, they argue.

3 Background

The models to be presented later are stylized and abstract from many factors which may matter for the likelihood of war: institutions is one example, in particular democracy.[3] They may nevertheless be a useful starting point. The mechanics that drive the results seem to have played a role in many phases of human history, and they may also have played a role in institu-

[3] Rummel (1997) emphasizes the link between dictatorship and genocide. Others have recently argued that particularly young and emerging democracies need not always be peaceful; see Mansfield and Snyder (2005).

tional development. We next discuss how the chains of causality at work in the models can be interpreted in terms of the historical facts. Two components are central to the story told here: the link from resource scarcity to conflict and war; and the role of technology as a factor both in easing resource competition, and raising the lethality of war.

3.1 Resource competition and war

The link from resource scarcity to conflict has been documented in the downfall of many ancient civilizations, e.g. the Roman Empire and Easter Island; several more examples are discussed in Jared Diamond's (2005) "Collapse." In modern times, population pressure continues to impact conflict propensity, in particular in poorer regions, more dependent on land and agriculture. Diamond (2005, Ch. 10) discusses overpopulation as a factor behind the 1994 genocide in Rwanda.[4] Miguel et al. (2004) find a strong negative effect of economic growth on the likelihood of outbreak of civil war among 41 African countries, using rainfall as an exogenous instrument. Friedman (2005) lists numerous examples of how rising living standards have made Western societies more open, democratic, and less prone to conflict.

In European history famine and high food prices have been a cause behind many episodes of social unrest; a prominent example is the French revolution in 1789 (Ponting 1991, p. 102-110). The European colonization of the rest of the world, and subsequent genocides, can be interpreted as an outcome of European population pressures and a hardening competition for land (Pomeranz 2001).

Early improvements in living standards from the 19th century may have begun to make Europe less war prone. From the end of the Franco-Prussian war of 1870-71 to the outbreak of WWI in 1914 Europe went through a phase of relative peace, with no wars fought which involved any of the great powers of Europe. Over these years trade increased, education levels rose, and many new technologies, such as railways and petrochemical inventions, made life

[4]Ethnic divides between Hutus and Tutsis played a role too but that cannot have been the only explanation, argues Diamond. For example, many killings took place where only Hutus lived.

better in Europe. (See e.g. Galor 2005 and further references therein.)

As a result of rising living standards, and reflecting the fact that these economies were still largely in a Malthusian equilibrium, population levels also rose rapidly in most European powers. However, there was a strong geographical imbalance in population growth rates across Europe. For example, Germany's population rose from about 40 million in 1870 to about 67 million in 1913, at the dawn of WWI. The corresponding population numbers for France was 37 million in 1870 and 40 million in 1913. (These numbers are from Mitchell 2003, Table A5; see also Browning 2002, Table 9). From a state of rough parity, Germany's population came to outnumber that of France.

Rapid industrialization and population growth also led to resource competition. Energy consumption (in particular coal) grew rapidly all over Europe, but again the divergence between France and Germany is striking: over the period 1890 to 1913 France's energy consumption rose by 80%, whereas that of Germany by 224% (Browning 2002, Table 10).

This was paralleled by Germany's emergence as a great power, and its search for "a place in the sun." Germany's hunger for natural resources played a role both in its competition for new colonies and its policies in Europe. Before WWI a group of influential land-owners and industrialists – known as the Pan-German League – had formulated an explicit war-aims program (see Hardach 1977, Ch. 8). Their program made explicit demands for territorial conquests, from Belgium to Russia, where the inhabitants were to be evacuated and replaced by Germans. Germany's land-owning elite (the Junkers) wanted more agrarian lands; the industrialists called for the annexation of territories rich in coal and iron-ore (cf. the citation of Walter Rathenau in the introduction). Indeed, the most resource rich regions of Europe, such as Saar and Silesia, were the most highly contested in WWI. In the Paris peace talks in 1919, France successfully insisted on control over Saar despite its population being predominantly German (thus breaking some of the core principles formulated by U.S. President Wilson).[5]

[5] McMillan (2001, p. 195) describes Saar as follows: "What had been a quite farming country with beautiful river valleys in the nineteenth century had become a major coal mining and manufacturing area in the nineteenth century. In 1919, when coal supplied

Competition for natural resources and land seems to have been important in other wars too, such as Japan's conquest and occupation of Manchuria. In the lead-up to the second world war Nazi rhetoric expressed a desire for more land and "space" (lebensraum). (See e.g. Ehrlich 2000, p. 270.) It is also worth noting that the most conflict-ridden region of the world today is the oil-rich Middle East.

3.2 Technology

These resources – coal, oil, metals, etc. – are here considered "scarce" in the sense that military powers have found it worthwhile to spend time and money to fight over them. This does not mean that they are, or ever were, running out. In fact, new discoveries have made some of these resources less scarce (or, rather, less important). In that sense, technological progress seems to mitigate resource scarcity. For example, the replacement of coal by oil as a major energy source seems to have ruled out any military contests over coal today.

As described, over the peaceful years 1871-1914 many new technologies made life better for many people in Europe. But new technologies also made WWI, once it broke out, to the most lethal war seen thus far. The inventions included mines, tanks, chemical weapons, and a number of improvements in existing technologies such as guns, gun powder, explosives, and artillery. Other innovations, such as radio and railways, played a role in mobilizing forces and spreading information and propaganda. (See e.g. Browning 2002, Ch. 4 for an overview.)

One can thus argue that a long phase of peace in Europe generated population growth and rising levels of technology, which made war more lethal once it eventually broke out. Europe today, however, seems to be on a type of peaceful growth path. Many of the (former) great military powers have more advanced nuclear, chemical and biological weapons technologies, than they ever had before, and these would obviously be very deadly if they were used in large scale warfare. However, no such wars are being fought in Europe today, at least among rich countries, arguably for the simple reason that

almost all of Europe's fuel needs, that made the region very valuable."

they are rich and prosperous. In sum, the effects of war are huge but the risk of war is vanishingly small.

There are also differences in the timing by which countries, or regions, become peaceful, which relates to the timing of economic development. As noted, the number of people killed in war and genocide in Europe dropped to zero in or around 1945 (the end of WWII). Thereafter, other regions of the world (like the Soviet Union and China) whose economic development has been lagging that of Europe and its offshoots, have continued or begun murderous phases similar to that of Europe during WWI and WWII. (See Figures 1a-c.) Africa may be passing a similar phase even later, with the genocide in Rwanda in 1994 and ongoing ethnic cleansing in Sudan. The good news is that this seems to be just a phase. If, in the limit, all countries become prosperous (cf. Lucas 2002, Ch. 4), this would mean that the world eventually becomes totally peaceful.[6]

4 A basic model

This section presents a basic model which can replicate many of the facts described above; later sections will then extend this setting in several ways. The framework is a two-period overlapping-generations model, where agents (referred to by the female pronoun) live as children and adults. Adults rear children, some of whom die before reaching adulthood. There are two sources of death: starvation and war. Those children who survive both war and starvation become adults in the next period.

The number of children born by each agent is exogenous and denoted $\overline{n}$. A fraction s_t of these children survive starvation. This fraction depends on time spent nurturing the children (e.g., keeping them clean), and on how well the children are fed.[7] How much food the parent can collect in turn depends

[6]This reasoning seems to abstract from terrorist networks working without any distinct home base. However, terrorists tend to be recruited from, if not poor, often less "modern" regions of the world (cf. Fukuyama and Samin 2002). If prosperity as a rule brings modernization, one may thus argue that there still exists a fully peaceful balanced growth path (which the world may be on in the distant future) where the whole world is rich, modern, and prosperous and the risk of terrorist attacks has vanished.

[7]The food collected could be thought of as being used either to feed the mother and

on her time spent competing for food. A time constraint requires that time spent nurturing children and in resource competition sum up to unity. The fraction children surviving starvation is assumed to be given by

$$s_t = q(c_t)[1 - r_t], \tag{1}$$

where r_t denotes time spent in resource competition (and $1 - r_t$ thus the time spent nurturing the offspring). The amount of food procured, c_t, determines survival through the function $q : \mathbf{R}_+ \to [0, 1)$.

The total land area from which food can be procured (i.e., collected, hunted, or produced using agriculture or horticulture), is normalized to one, and total (adult) population is denoted P_t. Although the land area is fixed the technology used to procure food evolves endogenously; A_t denotes the total amount of food generated by the unit-sized land in period t. The total pie of food or resources that agents compete over thus equals A_t, and in a symmetric equilibrium food per agent equals A_t/P_t.

Let the time spent by the average agent in resource competition be denoted R_t. Food collected by a single agent in period t who fights r_t units of time, while total resource competition by others amounts to $(P_t - 1)R_t$, is given by a Tullock-type of contest function:

$$c_t = \left[\frac{r_t}{r_t + (P_t - 1)R_t}\right] A_t. \tag{2}$$

Note that time spent in resource competition is a social waste, since each agent's time spent competing only lowers the share taken by other agents. The equilibrium condition, $r_t = R_t$, implies that $c_t = A_t/P_t$. If there is only one agent ($P_t = 1$) she takes the whole pie and needs not exert any time to fight for it.

4.1 Timing of events

Because there are two sources of death (starvation and war) we need to be precise about the timing of the events. In each period t, they unfold as follows.

thus prolong her life to rear more offspring, or used to feed the offspring directly (and perhaps give her more breast milk to feed her children). The point is that the more is the total amount of food collected, the larger fraction of the offspring survives.

1. Each adult agent bears $\overline{n}$ children and divides time between resource competition and nurturing children to maximize the children's survival rate from starvation, s_t, as given by (1).

2. War breaks out with probability, z_t. This probability is taken as given by each agent but depends on the equilibrium time agents spent in resource competition at stage 1.

3. If war breaks out, a fraction $1 - v_t$ of the $\overline{n}s_t$ children who survived starvation at stage 1 are killed. The war survival rate, v_t, is taken as given by each agent and depends on the level of technology. If there is no war, all $\overline{n}s_t$ children survive to become adults in the next period. Regardless of war or peace, the currently adult do not live to the next period, but die from old age.

4.1.1 Resource competition

Each agent chooses r_t so as to maximize her children's survival rate in (1), subject to (2). The solution is given by

$$g(c_t)\left(\frac{\partial c_t}{\partial r_t}\right)\frac{1-r_t}{c_t} = 1, \tag{3}$$

where $g(c)$ is the elasticity of $q(c)$ with respect to c:

$$g(c_t) = \frac{q'(c_t)c_t}{q(c_t)}. \tag{4}$$

In equilibrium, where $R_t = r_t$ and $c_t = A_t/P_t$, (3) becomes:[8]

$$g\left(\frac{A_t}{P_t}\right)\left(\frac{P_t-1}{P_t}\right)\left(\frac{1-R_t}{R_t}\right) = 1, \tag{5}$$

[8] It can be seen that

$$\frac{\partial c_t}{\partial r_t}\frac{1}{c_t} = \left(\frac{R_t}{r_t}\right)\left[\frac{P_t-1}{r_t+(P_t-1)R_t}\right],$$

which equals $(P_t-1)/(R_tP_t)$ when $R_t = r_t$.

which gives the representative agent's resource competition, R_t, as a function of P_t and A_t.

Consider the case when both A_t and P_t are large, so that $(P_t - 1)/P_t \approx 1$, and A_t/P_t is finite and positive. Then it follows from (5) that the relationship between R_t and per-agent consumption, $c_t = A_t/P_t$, can be positive or negative depending on the sign of $g'(c)$; as shown by Grossman and Mendoza (2003) to ensure that scarcity of resources leads to more fighting one must assume that $g'(c) < 0$.

For the rest of this paper the following functional form will be used, which satisfies the Grossman-Mendoza condition:

$$q(c) = \max\left\{0, \frac{c - \bar{c}}{c}\right\}, \tag{6}$$

where $\bar{c}$ will be called subsistence consumption. That is, the agent must procure more than $\bar{c}$ to have any chance of surviving starvation. If, in any period, A_t/P_t falls below $\bar{c}$ the whole population dies out. Note also that $q(c)$ goes to one as c goes to infinity.

Using (4), (5), and (6), it is seen that equilibrium time in resource competition equals:

$$R_t = \frac{\bar{c}\,(P_t - 1)}{A_t - \bar{c}} \equiv R(A_t, P_t). \tag{7}$$

Two details are worth noting. First, in an economy which exhibits sustained growth in per-capita consumption, c_t, meaning that A_t grows at a faster rate than P_t, the equilibrium time spent in resource competition, R_t, approaches zero. In that sense, this model has the feature that prosperity leads to peace.

The second detail worth noting is that R_t falls between zero and one, as long as $P_t > 1$, and $A_t/P_t < \bar{c}$.

Using (1), together with the equilibrium conditions $R_t = r_t$ and $c_t = A_t/P_t$, and (6) and (7), it is seen that the equilibrium survival rate from starvation becomes

$$s_t = q\left(\frac{A_t}{P_t}\right)[1 - R(A_t, P_t)] = \frac{(A_t - \bar{c}P_t)^2}{A_t\,(A_t - \bar{c})}. \tag{8}$$

4.1.2 War and peace

As described, in each period t war breaks out with probability z_t. In the real world, decisions by political leaders about going to war are affected by many factors, and involve complex political and social processes. As argued in Section 3, one factor that seems to have mattered in many historical contexts is competition for land and natural resources. The model presented thus far has a microeconomic link from resource scarcity to conflicts at the individual level, as seen from the expression for equilibrium resource competition in (7). The next step is to think about how such individual-level resource competition may spill over into war. Rather than confronting a host of theoretical issues regarding collective decision making, in this section the link from resource competition to the outbreak of war is treated in a black-boxed, but arguably quite plausible, fashion: the probability of war is simply assumed to depend on the degree of resource competition, R_t:

$$z_t = R_t^{\zeta}, \tag{9}$$

where $\zeta > 0$. Note that a society without resource competition ($R_t = 0$) is peaceful.

4.1.3 War casualties

Recall that a fraction v_t of the children survive war (if there is a war). To capture the idea that rising levels of technology have historically led to more lethal weapons and arms, v_t is assumed to be decreasing in the level of technology. This is also treated in a black-boxed fashion, given by this functional form:

$$v_t = \frac{\lambda + \delta A_t}{\lambda + A_t}, \tag{10}$$

for some $\lambda > 0$ and $\delta \in (0, 1/\overline{n})$. (The upper bound for δ is explained below.) Note that $\lim_{A_t \to \infty} v_t = \delta$; the parameter δ thus measures the fraction of the population who would survive if war were to break out in an economy with sustained growth in technology.

4.2 Population dynamics

In peace each adult agent has $\overline{n}s_t$ children who survive to adulthood. Thus, population evolves according to $P_{t+1} = P_t\overline{n}s_t$. In war a fraction $1 - v_t$ of the children are killed, so population evolves according to $P_{t+1} = P_t\overline{n}s_tv_t$. Using (8), (9), and (10), this gives the following dynamic equation for population:

$$P_{t+1} = \begin{cases} \overline{n}P_t\left(\frac{(A_t-\overline{c}P_t)^2}{A_t(A_t-\overline{c})}\right)\left(\frac{\lambda+\delta A_t}{\lambda+A_t}\right) & \text{with probability} \quad [R(A_t,P_t)]^\zeta \\ \\ \overline{n}P_t\left(\frac{(A_t-\overline{c}P_t)^2}{A_t(A_t-\overline{c})}\right) & \text{with probability} \quad 1-[R(A_t,P_t)]^\zeta \end{cases}. \tag{11}$$

4.3 Technology dynamics

The level of technology is assumed to evolve according to:

$$A_{t+1} = A_t^\alpha P_t^\beta \tag{12}$$

where $\alpha \in (0,1)$, $\beta > 0$, and $\alpha + \beta > 1$.

Letting population enter the dynamic equation for technology may capture a scale effect, à la e.g. Kremer (1993) and Jones (2001); the more people there are to make inventions and discoveries the faster is the rate of technological progress.

The parametric restriction that $\alpha + \beta > 1$ implies that there exists a peaceful balanced-growth path without resource competition, and where per-capita consumption, A_t/P_t, exhibits sustained growth.

Together, (11) and (12) constitute a stochastic two-dimensional system of difference equations. What path the economy follows depends on whether it is in a state of war or peace, and it switches between these states with a probability which in turn evolves endogenously over time.

4.3.1 Always war or always peace

First consider how an economy behaves if it is either in perpetual war or in perpetual peace. In the always-peace case, the economy exhibits sustained growth in A_t and P_t. Also, given the parametric assumptions made, A_t/P_t

exhibits sustained growth. To see this, note that in the limit the growth rate of technology equals

$$g^* = \overline{n}^{\frac{\beta}{1-\alpha}} > \overline{n}, \tag{13}$$

where the inequality follows from $\overline{n} > 1$, $\alpha \in (0, 1)$, and $\alpha + \beta > 1$. Recall from (8) that, if A_t/P_t exhibits sustained growth, the survival rate from starvation goes to one. Thus, on the balanced growth path population grows at rate $\overline{n}$ and the inequality in (13) ensures that A_t/P_t also goes to infinity.

In the always-war case, the assumption that $\delta < 1/\overline{n}$ rules out sustained growth in either A_t or P_t. Intuitively, when technology reaches high enough levels, warfare becomes so lethal that population begins to decline. To see this more formally, use the population dynamics under war in (11), i.e., $P_{t+1} = P_t \overline{n} s_t v_t$. Then recall from (10) that $v_t < \delta$, and from (8) that $s_t < 1$. Thus, $\delta < 1/\overline{n}$ implies $P_{t+1} < P_t$. Without sustained growth in P_t, it is seen from (12) and $\alpha < 1$ that there cannot be any sustained growth in A_t.

4.3.2 Switching between war and peace

Next, we simulate an economy which switches stochastically between war and peace, with the endogenous probability of war given by (7). More precisely, we let u_t be an i.i.d. random variable drawn from a uniform distribution on $[0, 1]$. War breaks out in period t if $u_t \leq R_t^{\zeta}$, which happens with probability R_t^{ζ}.

The results from one such simulation is seen in Figure 2. Technology and population endogenously transit onto sustained growth as wars become less frequent over time. On the balanced growth path technology grows at a faster rate than population (which follows from our assumptions about α and β). Therefore, consumption endogenously begins to grow at a sustained rate too. This makes resource competition and the probability of war decline over time. At the same time the death rate in war is rising, due to growth in technology. Thus, the expected war death rate (the probability of war times the death rate if war happens) is inversely U-shaped; it goes to zero in the limit because the probability of war goes to zero and the war death rate is bounded from above. In the panel showing the number of people killed in war, it is seen that wars are very frequent at first. Over time, wars become less frequent but also more lethal (more people are killed). Eventually, they stop occurring.

Aside from the shocks that affect war or peace, all variables which evolve over time do so endogenously, and interdependently: the paths for technology and population depend on whether there is war or peace; the probability of war depends on resource competition which in turn depends on technology and population.

Peace leads to population expansion, which has two effects. First, it makes resources become scarcer, which can generate two types of Malthusian backlash: food scarcity, leading to higher mortality in a conventional Malthusian fashion; and increased competition for resources, worsening the risk of war. At the same time, a population expansion can be self-perpetuating because it enables growth in technology, making resource scarcity decline, and the war risk go to zero; that way, prolonged peace can make the economy break out of its Malthusian trap.

Due to the random component determining war or peace all simulations look different from one another. However, the overall shape of the time paths is quite persistent. Figure 3 shows the time paths for consumption, the probability of war, and the number of killings, for three economies. These are identical aside from the realized shocks. As seen, the relative timing of the growth take-off is the same as for the decline in the probability of war. Note also that each country has its biggest spikes in killings late in its course of development, and that the latest spikes are associated with the latest economies to develop. This seems to fit with the stylized fact that the worst phases of war and genocide have occurred in connection to a take-off in growth, and have been followed by sustained growth and permanent peace (cf. Figures 1a-c).

Figure 4 shows the result of a Monte Carlo simulation, showing the time path for each variable, when averaged across 100 simulations. As seen the qualitative features are the same as when looking at one single run, but the paths are slightly smoother. The time horizon is extended to 1000 periods to make it possible to see the decline in killings for the latest economies to develop.

4.4 Discussion

(To be written...)

5 An extended model

The setting presented so far captures many empirically relevant mechanisms shaping conflict and economic development but also abstracts from many factors. For example, war is not modelled as a choice but assumed to break out as a result of resource competition. This section presents a model where the decision to wage war is modelled explicitly. To summarize, this setting extends the previous in three ways.

- **Land and conflict.** There are two countries and a fixed amount of land. The division of land between the two countries may change as the result of war. War amounts to one country attacking the other. The decision to wage war is done by the governments of each country, aiming at maximizing the expected utility of each of their respective country's representative agents.
- **Fertility and human capital.** Agents choose the number of children to rear and how much human capital to invest in each child. The level of technology determines the return to investing in children's human capital, so technological progress induces parents so substitute from quantity to quality of children.
- **Technological progress.** A country's technology either progresses at a rate which depends on the country's human capital (if the country innovates at home); or it can be copied from the other country.

5.1 Basics

The two countries are referred to as I and II. The total amount of land equals one. In period t the size of country j's territory is denoted by $m_{j,t}$ ($j =$I, II).

The timing of events is as follows.

1. Taking as given initial landholdings, technology, and population, the governments of the two countries choose whether or not to declare war on the other country. If no country declares war, peace prevails. In war some of the population of each country die and territory changes hands.

2. Given the updated distribution of territory across countries, and the updated size of the population (some of whom may have died in war), those agents who survived the war now compete domestically over the home country's resources. Resources per agent determine how many survive starvation.

3. Agents who have survived both war and starvation allocate their remaining time to rearing and educating children. This updates human capital and population to the next period. Technology is updated as well.

5.2 Human capital

Human capital in country j ($j =$I, II) of a representative agent who is adult in period t is denoted by $h_{j,t}$. Human capital transmitted to children, $h_{j,t+1}$, depends on four inputs: the total amount of time spent on all children's education, $e_{j,t}$; the number of children, $n_{j,t}$; the parent's own human capital, $h_{j,t}$; and the level of technology, $A_{j,t}$:

$$h_{j,t+1} = h(e_{j,t}, n_{j,t}, h_{j,t}, A_{j,t}), \tag{14}$$

for $j =$I, II.

In a standard way, it is assumed that $h(\cdot)$ is increasing in $e_{j,t}$ and $h_{j,t}$, and decreasing in $n_{j,t}$.

The somewhat novel ingredient in (14) is that technology, $A_{j,t}$, enters as an argument. The idea is similar to that of Galor and Weil (2000): technological progress increases the returns to human capital investment.[9] Moreover,

[9]Galor and Weil (2000) rather assume that technological change from period t to $t+1$ enters the production function for human capital. The formulation here generetates similar mechanics: a rise in technology in period t leads to more time invested in children's

here it is assumed that this effect sets in once technology has reached a certain threshold. More precisely,

$$\frac{\partial h(e,n,h,A)}{\partial e \partial A} \begin{cases} > 0 & \text{for } A \geq \widehat{A} \\ = 0 & \text{for } A < \widehat{A} \end{cases}, \tag{15}$$

where $\widehat{A} > 0$ is the exogenously given threshold. This generates the feature that fertility in country j stays constant up to the point in time when $A_{j,t}$ exceeds $\widehat{A}$, whereafter fertility starts to decline.

The following functional form for $h(\cdot)$ generates nice closed-form solutions:

$$h_{j,t+1} = B \left[\frac{e_{j,t}}{F(A_{j,t}) + n_{j,t}} \right] h_{j,t}^{\theta}, \tag{16}$$

where $B > 0$, $\theta \in (0,1)$, and the function $F : \mathbf{R}_+ \to \mathbf{R}_+$ satisfies

$$F'(A) \begin{cases} < 0 & \text{for } A \geq \widehat{A} \\ = 0 & \text{for } A < \widehat{A} \end{cases}. \tag{17}$$

It is then straightforward to verify that the production function in (16) satisfies the property in (15).[10]

The interpretation of (16) is that educating children exhibits scale effects. If children's human capital is proportional to education time per child, $e_{j,t}/n_{j,t}$, parents can make human capital per child arbitrarily large by setting fertility sufficiently small. Here the term $F(A_{j,t})$ imposes an upper bound on children's human capital, which is inversely related to $F(A_{j,t})$ and thus positively related to $A_{j,t}$.

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education in the same period; in the Galor-Weil model a rise in technology in period $t+1$ (holding fixed technology in period t) leads to more time invested in children's education in period t.

[10]To see see this note that for $A \geq \widehat{A}$,

$$\frac{\partial h(e,n,h,A)}{\partial e \partial A} = \frac{-Bh^{\theta} F'(A)}{[F(A)+n]^2} > 0.$$

As in the previous setting, $r_{j,t}$ denotes the amount of time the parent spends in resource competition. The total time endowment is set to unity so time spent on children's education equals

$$e_{j,t} = 1 - r_{j,t}. \tag{18}$$

Letting capital letters denote average levels it is noted that

$$H_{j,t+1} = B\left[\frac{1 - R_{j,t}}{F(A_{j,t}) + n_{j,t}}\right] H_{j,t}^{\theta}, \tag{19}$$

for j =I, II. Thus, resource competition is detrimental to human capital accumulation.

5.3 Technology

Technology in country j is updated either by domestic innovation or by copying country i. Using domestic innovation country j's technology grows at a rate which depends on its (initial) human capital level. If copying, country j acquires a fraction of the other country's technology (after it has been updated). The following production function is used:

$$A_{j,t+1} = \max\{(1 - \delta)A_{i,t+1}, A_{j,t}(1 + DH_{j,t})\} \tag{20}$$

for $(i, j) = \{(\text{I,II}), (\text{II,I})\}$, where $D > 0$ and $\delta \in [0, 1]$.

Thus, if its own levels of technology and human capital are large relative to that of the other country (that is, if $A_{j,t}[1+DH_{j,t}] > (1-\delta)A_{i,t}[1+DH_{i,t}]$) country j will innovate at home; else it will copy country i's technology. Setting $\delta = 1$ means copying never takes place; setting $\delta = 0$ one country will always copy the other.

5.4 Resource competition and the objective function

An agent in country j who survives war (if any) and starvation cares about her number of children, $n_{j,t}$, and the human capital of each child, $h_{j,t+1}$, according to this utility function:

$$U_{j,t} = h_{j,t+1} n_{j,t}^{\gamma}, \tag{21}$$

where $\gamma \in (0, 1)$.

The probability that the agent is alive equals the product of the probability of surviving starvation, and the probability of surviving war. As before, the probability of surviving starvation is denoted $q_{j,t}$, and $\upsilon_{j,t}$ denotes the probability of surviving a possible war (in peace $\upsilon_{j,t} = 1$). Setting utility in case of death (through war or starvation) to zero, expected utility is given by

$$E(U_{j,t}) = \upsilon_{j,t} q_{j,t} h_{j,t+1} n_{j,t}^{\gamma} + (1 - \upsilon_{j,t} q_{j,t}) \times 0. \tag{22}$$

The probability of surviving starvation takes the same form as in (6), that is:

$$q_{j,t} = \max\left\{0, \frac{c_{j,t} - \overline{c}}{c_{j,t}}\right\} \equiv q(c_{j,t}), \tag{23}$$

where consumption is now given by

$$c_{j,t} = \left[\frac{r_{j,t}}{r_{j,t} + R_{j,t}(\upsilon_{j,t} P_{j,t} - 1)}\right] m_{j,t} A_{j,t}, \tag{24}$$

where $R_{j,t}$ is average time spent in resource competition, $P_{j,t}$ is the pre-war population, and (recall) $m_{j,t}$ is the size of country j's territory. Thus, the total amount of resources equals $m_{j,t} A_{j,t}$, which is contested by the $\upsilon_{j,t} P_{j,t}$ agents who survived war.

5.4.1 Utility maximization

In the appendix it is shown that the first order-condition for fertility gives

$$n_{j,t} = \left(\frac{\gamma}{1 - \gamma}\right) F(A_{j,t}) \equiv n(A_{j,t}). \tag{25}$$

The optimal choice of $r_{j,t}$ boils down to maximizing $q(c_{j,t})(1 - r_{j,t})$ subject to (23) and (24); see (A1) in the appendix. This maximization problem is thus almost identical to that in Section 4. Analogously to (7), it can be seen that equilibrium in country j ($r_{j,t} = R_{j,t}$) gives the average time spent in resource competition as

$$R_{j,t} = \frac{\overline{c}\left[\upsilon_{j,t} P_{j,t} - 1\right]}{m_{j,t} A_{j,t} - \overline{c}}. \tag{26}$$

5.4.2 Consequences of war

Let S_t take the value 1 if there is war, and 0 if there is peace. As described already, war amounts to either country I attacking country II, or II attacking I. One country attacks the other country if, and only if, this raises the ex ante (pre-war) expected utility of the representative agent of the attacking country (but not necessarily the attacked).

The expected utility is given by (22), and depends on the war survival rate, $v_{j,t}$; and the updated landholdings, $m_{j,t}$ [via $c_{j,t}$; see (24)]. The next task is to specify functions for these variables.

The territorial conquest function In period t country j's landholdings are updated according to

$$\begin{aligned} m_{j,t} &= (1-\omega_{i,t})m_{j,t-1} + \omega_{j,t}m_{i,t-1} \\ &= (1-\omega_{i,t})m_{j,t-1} + \omega_{j,t}(1-m_{j,t-1}), \end{aligned} \tag{27}$$

where the second equality uses $m_{j,t} + m_{i,t} = 1$ in all periods, and $\omega_{j,t}$ denotes the fraction of country i's territory conquered by country j in case of war. This fraction depends on the relative levels of population and technology of the two belligerents, according to:

$$\begin{aligned} \omega_{j,t} &= S_t \left(\frac{\pi P_{j,t} A_{j,t}}{P_{i,t} A_{i,t} + \pi P_{j,t} A_{j,t}} \right) \\ &\equiv \omega(P_{j,t}, A_{j,t}, P_{i,t}, A_{i,t}, S_t), \end{aligned} \tag{28}$$

for $(i, j) = \{(\text{I,II}), (\text{II,I})\}$, where $\pi > 1$.

That is, peace means that no land changes hands ($S_t = 0$). In war ($S_t = 1$), the country with a higher $P_{j,t}A_{j,t}$ conquers a larger fraction of the other country's territory, compared to the fraction of its own land being lost to the other belligerent.

There is also an advantage of being the defender over the attacker: as long as $\pi > 1$ it is relatively easier to defend home territory than conquering foreign territory. The role of this parameter relates to that of Gonzales (2003), although the context is quite different. Here π captures an inherent advantage in armed conflict over a given territory, accruing to the party who already holds it; in Gonzales (2003) π rather measures the strength of legal or institutional protection of property rights.

The function which determines the territorial update for country j can be defined from (27) and (28) as

$$\begin{aligned} m_{j,t} &= [1-\omega(P_{i,t},A_{i,t},P_{j,t},A_{j,t},S_t)]\, m_{j,t-1} \\ &\quad +\omega(P_{j,t},A_{j,t},P_{i,t},A_{i,t},S_t)(1-m_{j,t-1}) \\ &\equiv \psi(m_{j,t-1},P_{j,t},A_{j,t},P_{i,t},A_{i,t},S_t). \end{aligned} \tag{29}$$

[Note that $\omega(P_{i,t},A_{i,t},P_{j,t},A_{j,t},S_t) \neq \omega(P_{j,t},A_{j,t},P_{i,t},A_{i,t},S_t)$, so the two terms do not cancel.]

The war survival probability function Recall that the fraction of country j's population surviving war is given by $\upsilon_{j,t}$, which depends on the technologies of the two belligerents, according to:

$$\upsilon_{j,t} = \frac{A_{j,t}}{A_{j,t}+\phi S_t A_{i,t}} \equiv \upsilon(A_{j,t},A_{i,t},S_t), \tag{30}$$

where $\phi > 0$. That is, more technologically advanced countries inflict greater casualties on their enemies, and are also better protected against own casualties. Note that peace ($S_t = 0$) implies zero war casualties (a war survival rate of one).

5.4.3 The decision whether or not to wage war

Expected utility in equilibrium To find the expected utility in equilibrium first set $r_{j,t} = R_{j,t}$ in (24) to get

$$c_{j,t} = \frac{m_{j,t}A_{j,t}}{\upsilon_{j,t}P_{j,t}}. \tag{31}$$

Then use (23) to note that, as long as $c_{j,t} > \overline{c}$, the survival probability becomes

$$q_{j,t} = \frac{c_{j,t}-\overline{c}}{c_{j,t}} = \frac{m_{j,t}A_{j,t}-\overline{c}\upsilon_{j,t}P_{j,t}}{m_{j,t}A_{j,t}}. \tag{32}$$

Using (26), one can derive $1 - R_{j,t} = (m_{j,t}A_{j,t} - \bar{c}\upsilon_{j,t}P_{j,t})/(m_{j,t}A_{j,t} - \bar{c})$. Using the expression for the survival probability in (32), and the expression for optimal fertility in (25), after some algebra (see the appendix) it is seen that the expected utility in equilibrium equals $BH_{j,t}^{\theta}$ times

$$\Psi(\upsilon_{j,t}, m_{j,t}, A_{j,t}, P_{j,t}) = \upsilon_{j,t}\left[\frac{1-\gamma}{F(A_{j,t})}\right]\left[\frac{(m_{j,t}A_{j,t} - \bar{c}\upsilon_{j,t}P_{j,t})^2}{m_{j,t}A_{j,t}\,(m_{j,t}A_{j,t} - \bar{c})}\right]. \tag{33}$$

Next use the function determining territorial conquests in (29), and the war survival rate in (30), together with (33) above, to define:

$$\begin{aligned} & \Phi(m_{j,t-1}, P_{j,t}, A_{j,t}, P_{i,t}, A_{i,t}, S_t) \qquad (34) \\ \equiv\ & \Psi(\upsilon(A_{j,t}, A_{i,t}, S_t), \psi(m_{j,t-1}, P_{j,t}, A_{j,t}, P_{i,t}, A_{i,t}, S_t), A_{j,t}, P_{j,t}). \end{aligned}$$

The function $\Phi(\cdot)$ is proportional to the expected utility in equilibrium, attained by agents in countries I and II, as a function of whether there is war or peace, as captured by S_t; and five state variables: $m_{\mathsf{I},t-1}$, $A_{\mathsf{I},t}$, $P_{\mathsf{I},t}$, $A_{\mathsf{II},t}$, $P_{\mathsf{II},t}$.[11]

Comparing payoffs from war and peace As described, a government (or other collective body) of each country chooses to go to war if doing so generates a higher expected utility to the representative agent. Define the set $\mathcal{P}_j$ as

$$\mathcal{P}_j = \left\{ \begin{array}{c} (m_{j,t-1}, P_{j,t}, A_{j,t}, P_{i,t}, A_{i,t}) \in [0,1] \times \mathbf{R}_+^4 : \\ \Phi(m_{j,t-1}, P_{j,t}, A_{j,t}, P_{i,t}, A_{i,t}, 0) > \Phi(m_{j,t-1}, P_{j,t}, A_{j,t}, P_{i,t}, A_{i,t}, 1) \end{array} \right\}. \tag{35}$$

In words, $\mathcal{P}_j$ is country j's "peace state," that is, the set of values that the five state variables $(m_{j,t-1}, P_{j,t}, A_{j,t}, P_{i,t}, A_{i,t})$ can take for country j not to declare war on country i.

Peace prevails when neither country attacks the other, which occurs if both $(m_{\mathsf{I},t-1}, P_{\mathsf{I},t}, A_{\mathsf{I},t}, P_{\mathsf{II},t}, A_{\mathsf{II},t}) \in \mathcal{P}_{\mathsf{I}}$ and $(1 - m_{\mathsf{I},t-1}, P_{\mathsf{II},t}, A_{\mathsf{II},t}, P_{\mathsf{I},t}, A_{\mathsf{I},t}) \in$

[11] There are actually eight state variables in total. However, $m_{\mathsf{I},t-1}$ determines $m_{\mathsf{II},t-1}$ since they sum up to unity; and $H_{\mathsf{I},t}$ and $H_{\mathsf{II},t}$ do not have any impact on the the relative payoffs of war and peace.

$\mathcal{P}_{\mathsf{II}}$. Thus, S_t can be written as a function of $m_{\mathsf{I},t-1}$, $P_{\mathsf{I},t}$,$A_{\mathsf{I},t}$, $P_{\mathsf{II},t}$, $A_{\mathsf{II},t}$, as follows:

$$\begin{aligned} S_t &= \left\{ \begin{array}{cc} 0 & \begin{array}{c} \text{if } (m_{j,t-1}, P_{j,t}, A_{j,t}, P_{i,t}, A_{i,t}) \in \mathcal{P}_j \\ \text{for } (i,j) = \{(\text{I,II}), (\text{II,I})\} \end{array} \\ 1 & \text{otherwise} \end{array} \right\} \\ &\equiv S(m_{\mathsf{I},t-1}, P_{\mathsf{I},t}, A_{\mathsf{I},t}, P_{\mathsf{II},t}, A_{\mathsf{II},t}). \end{aligned} \tag{36}$$

Note that the function $S(\cdot)$ is not symmetric; shifting order on e.g. $P_{\mathsf{I},t}$ and $P_{\mathsf{II},t}$ changes the value S_t takes. Intuitively, one country preferring peace does not mean the other country does. This complicates matters slightly in terms of writing the dynamical system.

5.4.4 The dynamical system

As shown in the appendix the model can be solved for a seven-dimensional system of difference equations as follows:

$$\begin{aligned} m_{\mathsf{I},t} &= \Pi(m_{\mathsf{I},t-1}, P_{\mathsf{I},t}, A_{\mathsf{I},t}, P_{\mathsf{II},t}, A_{\mathsf{II},t}) \\ P_{\mathsf{I},t+1} &= \Upsilon(m_{\mathsf{I},t-1}, P_{\mathsf{I},t}, A_{\mathsf{I},t}, P_{\mathsf{II},t}, A_{\mathsf{II},t}) \\ P_{\mathsf{II},t+1} &= \Upsilon(1 - m_{\mathsf{I},t-1}, P_{\mathsf{II},t}, A_{\mathsf{II},t}, P_{\mathsf{I},t}, A_{\mathsf{I},t}) \\ A_{\mathsf{I},t+1} &= \Lambda(A_{\mathsf{I},t}, A_{\mathsf{II},t}, H_{\mathsf{I},t}, H_{\mathsf{II},t}) \\ A_{\mathsf{II},t+1} &= \Lambda(A_{\mathsf{II},t}, A_{\mathsf{I},t}, H_{\mathsf{II},t}, H_{\mathsf{I},t}) \\ H_{\mathsf{I},t+1} &= \Gamma(m_{\mathsf{I},t-1}, A_{\mathsf{I},t}, P_{\mathsf{I},t}, A_{\mathsf{II},t}, P_{\mathsf{II},t}) \\ H_{\mathsf{II},t+1} &= \Gamma(1 - m_{\mathsf{I},t-1}, A_{\mathsf{II},t}, P_{\mathsf{II},t}, A_{\mathsf{I},t}, P_{\mathsf{I},t}), \end{aligned} \tag{37}$$

where the functions involved are defined in equations (A5), (A6), (A10), and (A11) in the appendix.

Some intuition...(to be written)

5.5 Quantitative analysis

Next the behavior of this economy is illustrated in a simulation.

Most functions have been given specific forms already. The exception is $F(A)$ appearing in the human capital production function in (16); recall from (25) that this in turn determines fertility. We shall use the following functional form:

$$F(A) = \overline{F} + (\underline{F} - \overline{F}) \max \left\{ 0, \frac{A - \widehat{A}}{A} \right\}, \tag{38}$$

where $\underline{F} < \overline{F}$. Note that $F(A) = \underline{F}$ for $A \leq \widehat{A}$; $F'(A) < 0$ for $A > \widehat{A}$; and $\lim_{A \to \infty} F(A) = \underline{F}$.

From (25) is seen that these features translate into fertility behavior: $n(A) = \overline{n} \equiv \gamma \overline{F}/(1-\gamma)$ for $A \leq \widehat{A}$; $n'(A) < 0$ for $A > \widehat{A}$; and $\lim_{A \to \infty} n(A) = \underline{n} \equiv \gamma \underline{F}/(1-\gamma)$.

The first step to simulate the model is to choose parameters values. Here these are chosen arbitrarily (to be done more carefully soon....)

Given parameter values the simulation algorithm is straightforward: first pick initial values, then update using the difference equations in (37), and iterate.

The parameter values in this example are chosen as in Table 1, most of them arbitrarily but some with specific targets in mind (more to be added...).

The result of this preliminary simulation is shown in Figure 6. It is assumed that each period is 5 years long. This may seem short considering the overlapping-generations structure of the model. However, it can be seen that a "perpetual youth" setting in which agents face a constant probability of death after childhood generates similar structures (more to be added...). Also, the length of most wars and genocides in the 20th century lasted about five years (at least more in that order of magnitude than a full generation of 20 years, or so).

The years are chosen so that the peak in the number of people killed, which is computed as $(1 - \upsilon_{j,t})P_{j,t}$, occurs in 1945; cf Figure 1a.

Initial conditions are here set so that both countries have the same initial technology, set to 25% of the threshold $\widehat{A}$ (above which fertility starts to decline).

Country I is initially allocated 0.6 of the unity-sized landmass, and country II the remainder 0.4. Levels of population and human capital are set at the steady state values associated with a dynamical system in which technology and land allocations are constant at their initial levels. Since both countries have the same technology, the country with the larger territory (country I in this case) thus has a larger initial population.

The patterns in Figure 6 are qualitatively consistent with the patterns in Figures 1a-c. The number of people killed peaks in 1945 (as calibrated) and the decline in fertility starts in 1930. The model can thus generate a simultaneous rise in war and genocide deaths together with an ongoing demographic transition.

Right after 1945 killings drop to zero. At this point no country chooses to start a war. Simultaneously levels of consumption (which would correspond to per-capita income levels) start to rise, which is due to the onset of the demographic transition, generating more human capital as investment in children and an associated spurt in technological progress.

6 Conclusions

To be written...

A Appendix

A.1 Optimality conditions in the extended model

Substituting (16), (18), and (24) into (22) it is seen that (conditional on having survived war) the agent's problem thus amounts to maximizing:

$$\max_{(r_{j,t},n_{j,t})\in[0,1]\times \mathrm{R}_+} \upsilon_{j,t} q\left(\frac{r_{j,t} m_{j,t} A_{j,t}}{r_{j,t}+R_{j,t}(\upsilon_{j,t}P_{j,t}-1)}\right)\frac{B(1-r_{j,t})h^{\theta}_{j,t}n^{\gamma}_{j,t}}{F(A_{j,t})+n_{j,t}}, \qquad \text{(A1)}$$

where $q(\cdot)$ is given in (23).

The first order condition for fertility can be written

$$\upsilon_{j,t} q(c_{j,t}) B(1-r_{j,t})\left\{\frac{\gamma n^{\gamma-1}_{j,t}\left[F(A_{j,t})+n_{j,t}\right]-n^{\gamma}_{j,t}}{\left[F(A_{j,t})+n_{j,t}\right]^2}\right\} h^{\theta}_{j,t}=0, \qquad \text{(A2)}$$

which gives (25).

A.2 The dynamical system in the extended model

There are seven state variables in total: $A_{\mathsf{I},t}, A_{\mathsf{II},t}, P_{\mathsf{I},t}, P_{\mathsf{II},t}, H_{\mathsf{I},t}, H_{\mathsf{II},t}$, and $m_{\mathsf{I},t}$. (Recall that $m_{\mathsf{I},t}$ determines $m_{\mathsf{II},t}$ from $m_{\mathsf{I},t} + m_{\mathsf{II},t} = 1$.) For each pair there is a difference equation, "mirrored" across the two countries.

A.2.1 Population

Population evolves according to $P_{j,t+1} = \upsilon_{j,t} q_{j,t} n_{j,t} P_{j,t}$. Substitute the survival rate in war in (30), and the territorial conquest function in (29), into the survival function in (32) to write:

$$\begin{aligned} & q_{j,t} \\ = \; & \frac{\psi(m_{j,t-1}, P_{j,t}, A_{j,t}, P_{i,t}, A_{i,t}, S_t) A_{j,t} - \bar{c}\upsilon(A_{j,t}, A_{i,t}, S_t) P_{j,t}}{\psi(m_{j,t-1}, P_{j,t}, A_{j,t}, P_{i,t}, A_{i,t}, S_t) A_{j,t}} \\ \equiv \; & \xi(m_{j,t-1}, P_{j,t}, A_{j,t}, P_{i,t}, A_{i,t}, S_t). \end{aligned} \tag{A3}$$

Next use the fertility function in (25), the expression for $q_{j,t}$ above, and the war survival function in (30) again. It is now possible to write $P_{j,t+1} = \upsilon_{j,t} q_{j,t} n_{j,t} P_{j,t}$ as

$$\begin{aligned} & P_{j,t+1} \\ = \; & \upsilon(A_{j,t}, A_{i,t}, S_t)\xi(m_{j,t-1}, P_{j,t}, A_{j,t}, P_{i,t}, A_{i,t}, S_t) n(A_{j,t}) P_{j,t} \\ \equiv \; & \widetilde{\Upsilon}(m_{j,t-1}, P_{j,t}, A_{j,t}, P_{i,t}, A_{i,t}, S_t) \end{aligned} \tag{A4}$$

The last step is to substitute for S_t using (36). The difference equation for $P_{\mathsf{I},t+1}$ can then be written

$$\begin{gathered} P_{\mathsf{I},t+1} \\ = \widetilde{\Upsilon}(m_{\mathsf{I},t-1}, P_{\mathsf{I},t}, A_{\mathsf{I},t}, P_{\mathsf{II},t}, A_{\mathsf{II},t}, S(m_{\mathsf{I},t-1}, P_{\mathsf{I},t}, A_{\mathsf{I},t}, P_{\mathsf{II},t}, A_{\mathsf{II},t})) \\ \equiv \Upsilon(m_{\mathsf{I},t-1}, P_{\mathsf{I},t}, A_{\mathsf{I},t}, P_{\mathsf{II},t}, A_{\mathsf{II},t}) \end{gathered} \tag{A5}$$

and similarly for $P_{\mathsf{II},t+1}$ (but mirror imaged).

A.2.2 Technology

When updating technology in (20), note that both countries cannot copy each other (as long as $\delta < 1$). Thus, if country j copies country i [$A_{j,t+1} =$

$(1-\delta)A_{i,t+1}]$ it must hold that country i updates its technology through innovation $[A_{i,t+1} = A_{i,t}(1 + DH_{i,t})]$, and vice versa. It is thus possible to rewrite (20) as

$$\begin{aligned} A_{j,t+1} &= \left\{ \begin{array}{cc} (1-\delta)A_{i,t}(1+DH_{i,t}) & \text{if } \frac{A_{j,t}(1+DH_{j,t})}{A_{i,t}(1+DH_{i,t})} < 1-\delta \\ A_{j,t}(1+DH_{j,t}) & \text{if } \frac{A_{j,t}(1+DH_{j,t})}{A_{i,t}(1+DH_{i,t})} \geq 1-\delta \end{array} \right\} \\ &\equiv \Lambda(A_{j,t}, A_{i,t}, H_{j,t}, H_{i,t}). \end{aligned} \tag{A6}$$

A.2.3 Human capital

To derive a dynamic equation for human capital start with (19). Using the expression for time spent in resource competition in (26), and fertility in (25), note that

$$\frac{1-R_{j,t}}{F(A_{j,t}) + n_{j,t}} = \frac{m_{j,t}A_{j,t} - \bar{c}\upsilon_{j,t}P_{j,t}}{[m_{j,t}A_{j,t} - \bar{c}]\,[F(A_{j,t}) + n(A_{j,t})]}, \tag{A7}$$

Substituting into (19) gives

$$\begin{aligned} H_{j,t+1} &= B\left[\frac{1-R_{j,t}}{F(A_{j,t}) + n_{j,t}}\right] H_{j,t}^{\theta} \\ &= \frac{B\,[m_{j,t}A_{j,t} - \bar{c}\upsilon_{j,t}P_{j,t}]\,H_{j,t}^{\theta}}{[m_{j,t}A_{j,t} - \bar{c}]\,[F(A_{j,t}) + n(A_{j,t})]} \\ &\equiv \tilde{\tilde{\Gamma}}(\upsilon_{j,t}, m_{j,t}, A_{j,t}, P_{j,t}, A_{i,t}, P_{i,t}). \end{aligned} \tag{A8}$$

After substituting the territorial conquest function in (29) for $m_{j,t}$, and the war survival rate in (30) for $\upsilon_{j,t}$, we can define:

$$\begin{aligned} & H_{j,t+1} \\ = \;& \tilde{\Gamma}(m_{j,t-1}, A_{j,t}, P_{j,t}, A_{i,t}, P_{i,t}, S_t) \\ \equiv \;& \tilde{\tilde{\Gamma}}\{\upsilon(A_{j,t}, A_{i,t}, S_t), \psi(m_{j,t-1}, P_{j,t}, A_{j,t}, P_{i,t}, A_{i,t}, S_t), A_{j,t}, P_{j,t}, A_{i,t}, P_{i,t}\}. \end{aligned} \tag{A9}$$

The last step is to substitute for S_t in (36) to write

$$\begin{aligned} & H_{\mathsf{I},t+1} \\ = \;& \tilde{\Gamma}(m_{\mathsf{I},t-1}, A_{\mathsf{I},t}, P_{\mathsf{I},t}, A_{\mathsf{II},t}, P_{\mathsf{II},t}, S(m_{\mathsf{I},t-1}, P_{\mathsf{I},t}, A_{\mathsf{I},t}, P_{\mathsf{II},t}, A_{\mathsf{II},t})) \\ \equiv \;& \Gamma(m_{\mathsf{I},t-1}, A_{\mathsf{I},t}, P_{\mathsf{I},t}, A_{\mathsf{II},t}, P_{\mathsf{II},t}), \end{aligned} \tag{A10}$$

and similarly for country II.

A.2.4 Territorial distribution

The dynamic equation for $m_{\mathsf{I},t}$ is given by (29) substituting for S_t using (36), that is:

$$\begin{aligned} & m_{\mathsf{I},t} \\ = \;& \psi(m_{\mathsf{I},t-1}, P_{\mathsf{I},t}, A_{\mathsf{I},t}, P_{\mathsf{II},t}, A_{\mathsf{II},t}, S(m_{\mathsf{I},t-1}, P_{\mathsf{I},t}, A_{\mathsf{I},t}, P_{\mathsf{II},t}, A_{\mathsf{II},t})) \\ \equiv \;& \Pi(m_{\mathsf{I},t-1}, P_{\mathsf{I},t}, A_{\mathsf{I},t}, P_{\mathsf{II},t}, A_{\mathsf{II},t}). \end{aligned} \tag{A11}$$

A.2.5 The full dynamical system

The dynamical system consists of seven difference equations which determine $m_{\mathsf{I},t}$, $P_{\mathsf{I},t+1}$, $A_{\mathsf{I},t+1}$, $H_{\mathsf{I},t+1}$, $P_{\mathsf{II},t+1}$, $A_{\mathsf{II},t+1}$, and $H_{\mathsf{II},t+1}$ as functions of the same variables dated one period back. Using the functions defined above this system can be written is (37).

References

[1] Brander, J.A., and M.S. Taylor, 1998, The simple economics of Easter Island: A Ricardo-Malthus model of renewable resource use, American Economic Review 88, 119-138.

[2] Browning, P., 2002, The changing nature of warfare – the development of land warfare from 1792 to 1945, Cambridge University Press, Cambridge, United Kingdom.

[3] Cervellati, M., and U. Sunde, 2005, Human capital formation, life expectancy, and the process of development, American Economic Review 95, 1653-1672.

[4] Collier, P. and A. Hoeffler, 1998, On economic causes of civil war, Oxford Economic Papers 50, 563-573.

[5] —–, 2004, Greed and Grievance in Civil Wars, Oxford Economic Papers 56, 663-595.

[6] Diamond, J., 2005, Collapse – how societies choose to fail or succeed, Viking Penguin, New York.

[7] Ehrlich, P.R., 2000, Human natures – genes, cultures, and human prospects, Penguin Books, New York.

[8] Friedman, B.M., 2005, The Moral Consequences of Economic Growth, Alfred A. Knopf, Random House.

[9] Fukuyama, F., and Samin, N., 2002, Modernizing islam, Commentary 114.

[10] Galor, O., 2005, Transitions, in: Aghion, P., and S. Durlauf (eds.), Handbook of Economic Growth, North-Holland.

[11] Galor, O., and O. Moav, 2002, Natural selection and the origin of economic growth, Quarterly Journal of Economics 117, 1133-1192.

[12] Galor, O., and D. Weil, 2000, Population, technology, and growth: from Malthusian stagnation to the demographic transition and beyond, American Economic Review 90, 806-829.

[13] Grossman, H.I., 1991, A general equilibrium model of insurrections, American Economic Review 81, 913-921.

[14] Grossman, H.I., and M. Kim, 1995, Swords and plowshares? A theory of the security of claims to property, Journal of Political Economy 103, 1275-1288.

[15] Grossman, H., and J. Mendoza, 2003, Scarcity and appropriative competition, European Journal of Political Economy 19, 747-758.

[16] Hansen, G.D., and E.C. Prescott, 2002, Malthus to Solow, American Economic Review 92, 1205-1217.

[17] Hardach, G., 1977, The first world war – 1914-1918, University of California Press, Berkley and Los Angeles.

[18] Hirschleifer, J., 1988, The analytics of continuing conflict, Synthese 76, 201-233.

[19] —–, 2001, The dark side of the force - economic foundations of conflict theory, Cambridge University Press.

[20] Johnson, N., M. Spagat, J. Restrepo, J. Bohórquez, N. Suárez, E. Restrepo, and R. Zarama, From old wars to new wars and global terrorism, mimeo, Royal Holloway.

[21] Jones, C., 2001, Was the industrial revolution inevitable? Economic growth over the very long run, Advances in Macroeconomics 1, 1-43.

[22] Kremer, M., 1993, Population growth and technological change: one million B.C. to 1990, Quarterly Journal of Economics 108, 681-716.

[23] Lagerlöf, 2003a, From Malthus to modern growth: can epidemics explain the three regimes?, International Economic Review 44, 2003, pp. 755-777.

[24] ——, 2003b, Mortality and early growth in England, Sweden, and France, Scandinavian Journal of Economics 105, 2003, pp. 419-439.

[25] Lucas, R.E., 2002, Lectures on Economic Growth, Harvard University Press.

[26] Mansfield, E.D., and J. Snyder, 2005, Electing to fight: why emerging democracies go to war, MIT Press.

[27] Marshall, M.G., and T.Ro. Gurr, 2005, A global survey of armed conflicts, self-determination movements, and democracy peace and conflict, Report published by CIDCM Center for International Development & Conflict Management University of Maryland, College Park, http://www.cidcm.umd.edu.

[28] McMillan, M., 2001, Paris 1919 – six months that changed the world, Random House, New York.

[29] Miguel, E., S. Satyanath, and E. Sergenti, Economic shocks and civil conflict: an instrumental variables approach, Journal of Political Economy 112, 725-753.

[30] Mitchell, B.R., 2003, International historical statistics – Europe 1750-2000, Palgrave-McMillan, New York.

[31] Pomeranz, K., 2001, The great divergence: China, Europe, and the making of the modern world economy, Princeton University Press.

[32] Ponting, C., 1991, A green history of the world – the environment and the collapse of great civilizations, St. Martin's Press, New York.

[33] Rummel, R.J., 1997, Statistics of democide – genocide and mass murder since 1900, University of Virginia, Charlottesville, Virginia 22903-1789.

[34] Tamura, R., 1996, From decay to growth: a demographic transition to economic growth, Journal of Economic Dynamics and Control 20, 1237-1261.

[35] ——, 2002, Human capital and the switch from agriculture to industry, Journal of Economic Dynamics and Control 27, 207-242.

Parameter	Value	From function
B	1.1	Human capital production function in (16) and (38)
θ	0.65	
$\overline{F}$	1.2	
$\underline{F}$	1	
$\widehat{A}$	10^{12}	
$\overline{c}$	0.1	Starvation survival function in (23)
δ	0.95	Technological updating in (20) or (A6)
D	2	
γ	0.5	Utility function in(21); see also max program in (A1)
π	15	Territorial conquest function in (28)
ϕ	10^{-10}	War survival function in (30)

Table 1: Parameter values in extended setting.

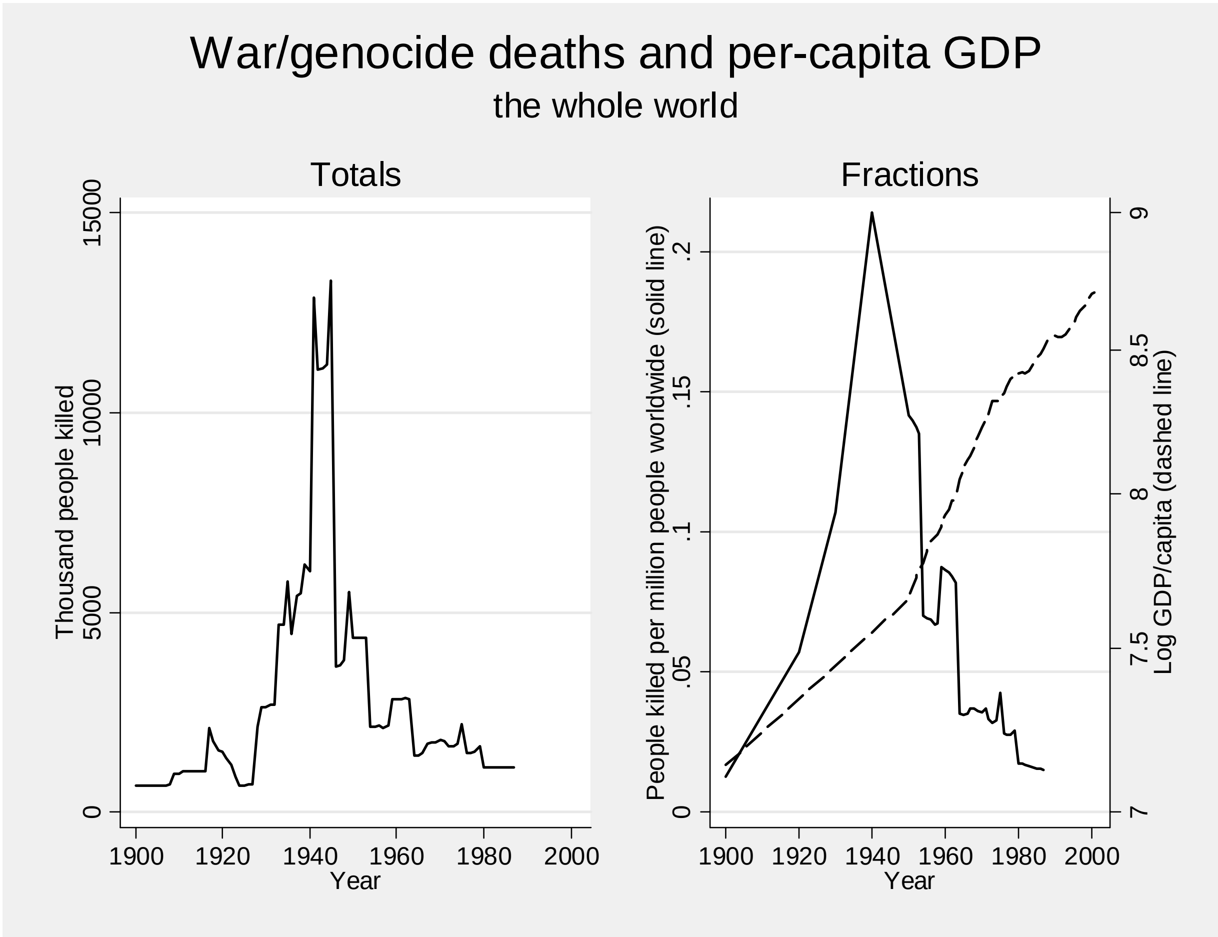

Figure 1a. War and genocide: total body count (left) and share of world population (right), and levels of GDP per capita. Sources: Rummel (1997) and Maddison (2004)

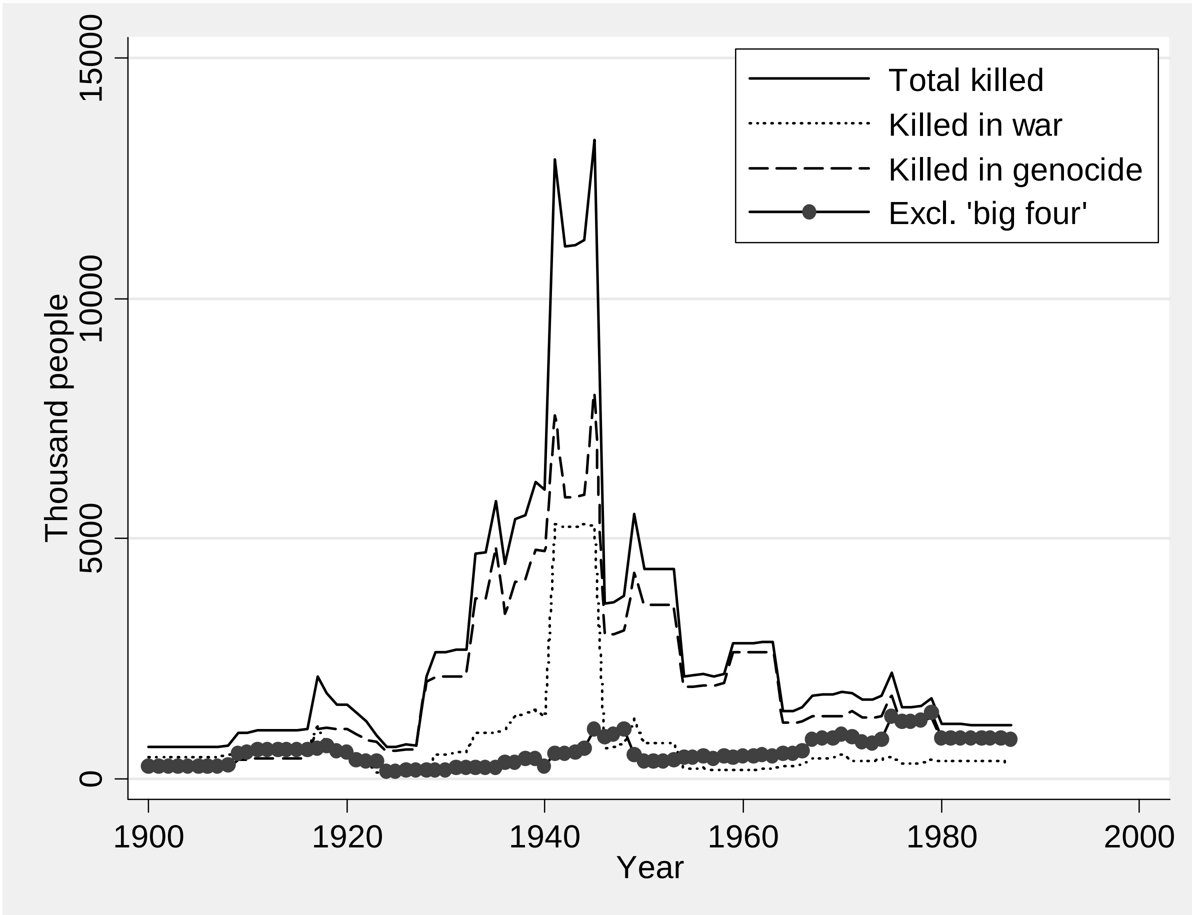

Figure 1b. Time paths for total killings, and for war and genocide killings separately. The time path for total killings excluding the four worst regions (Japan, Germany, Russia, and China) is also shown. Sources same as in Figure 1a.

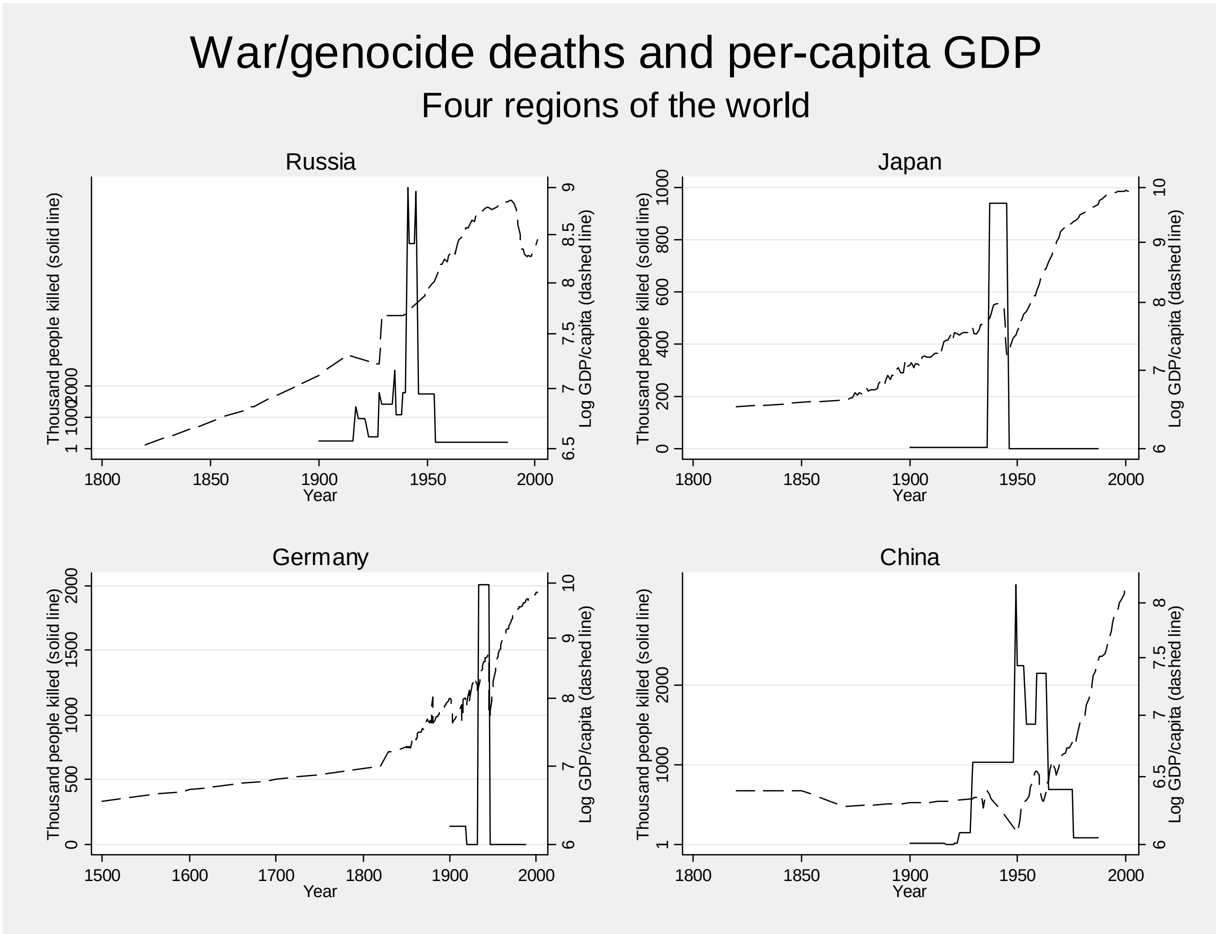

Figure 1c. War and genocide deaths and GDP per capita for the four worst regions. Sources same as in Figure 1a. Note the difference in time scale: the earliest income data is from 1500 for Germany and 1820 for the other three.

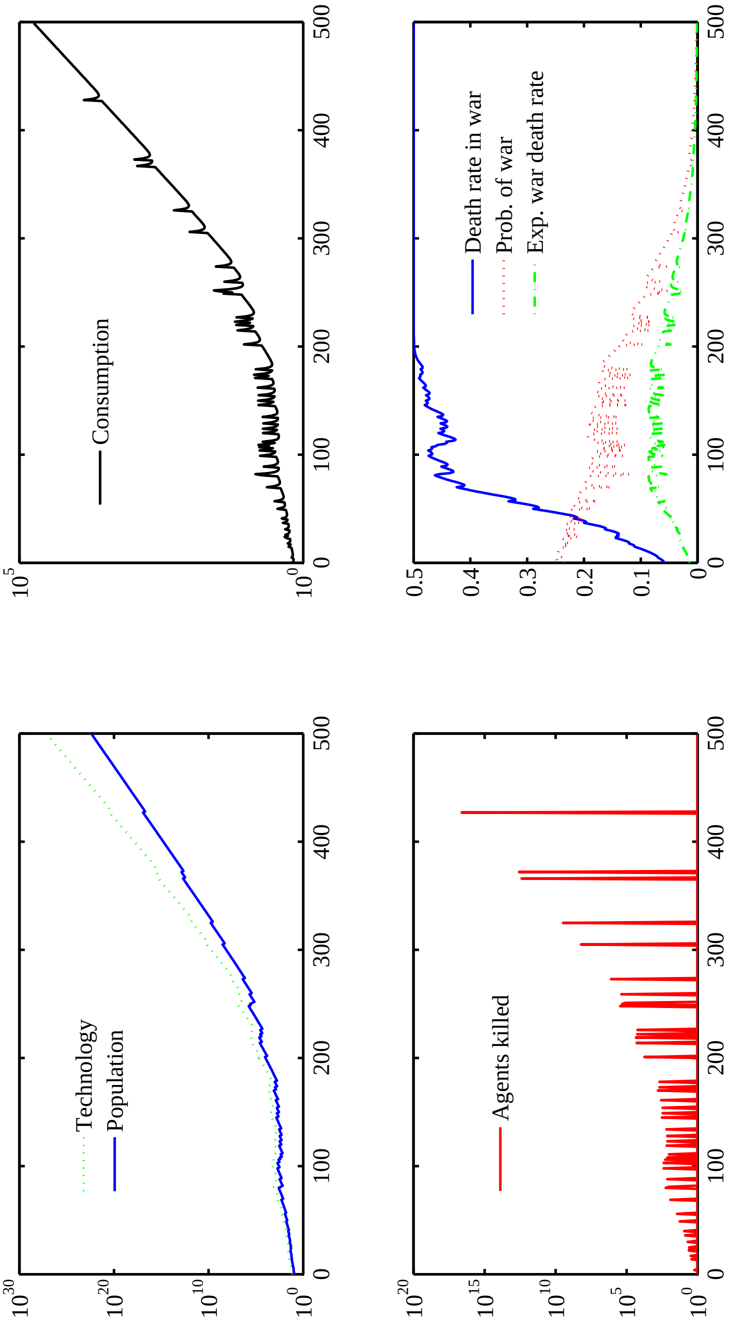

Figure 2: One single run.

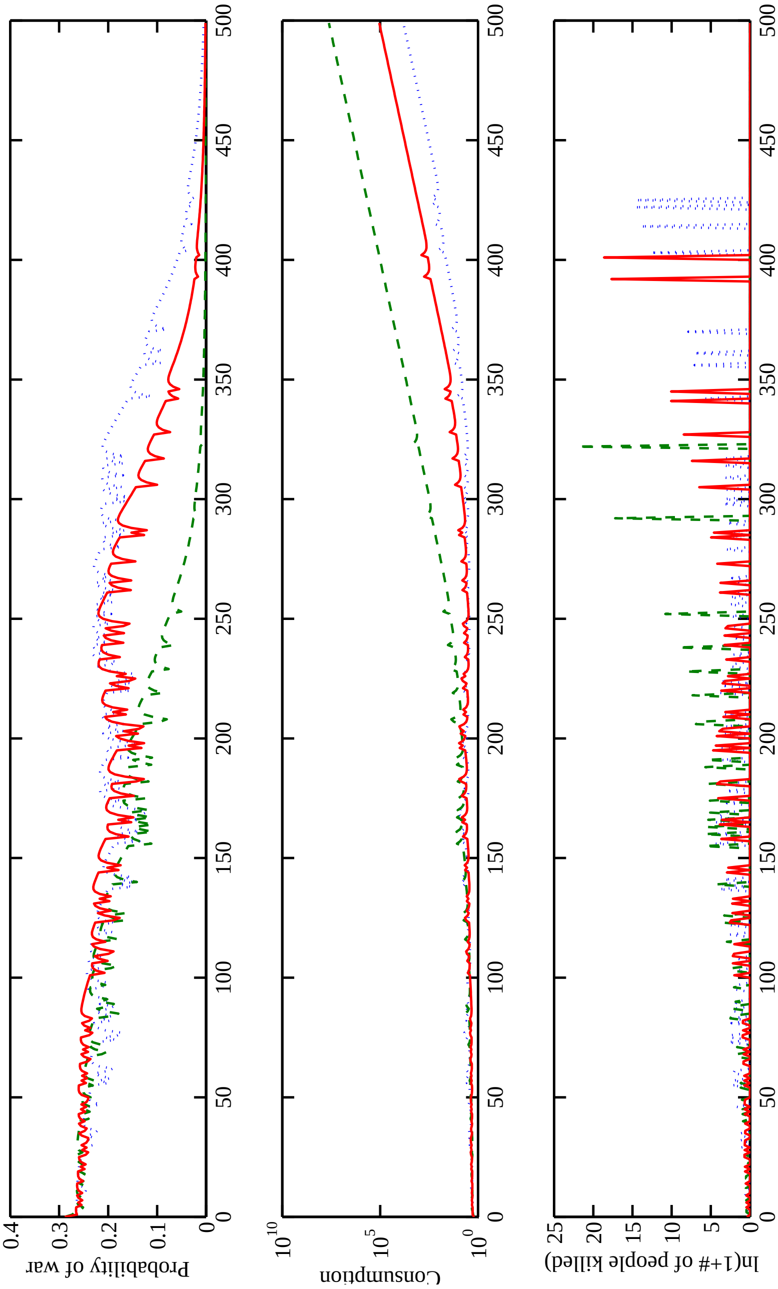

Figure 3: Three different runs.

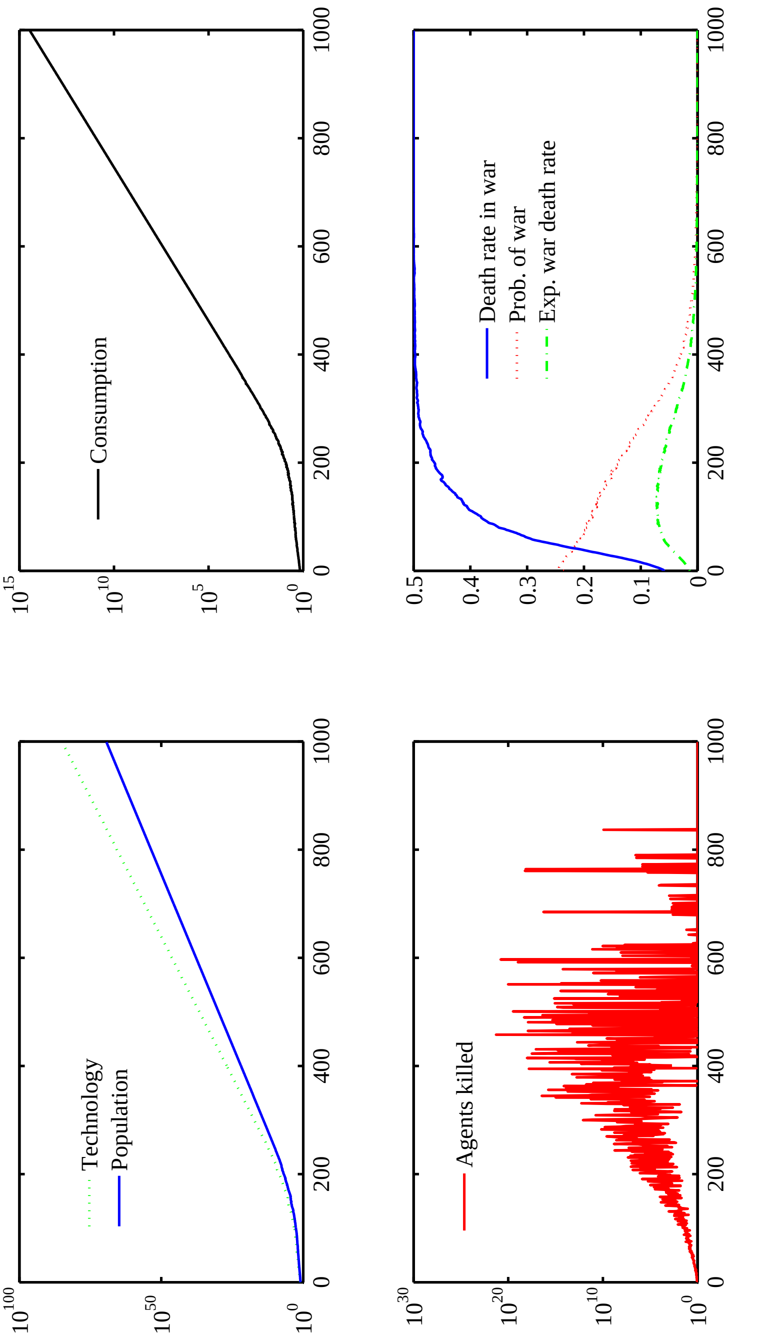

Figure 4: Monte-Carlo exercise (mean across 100 runs).

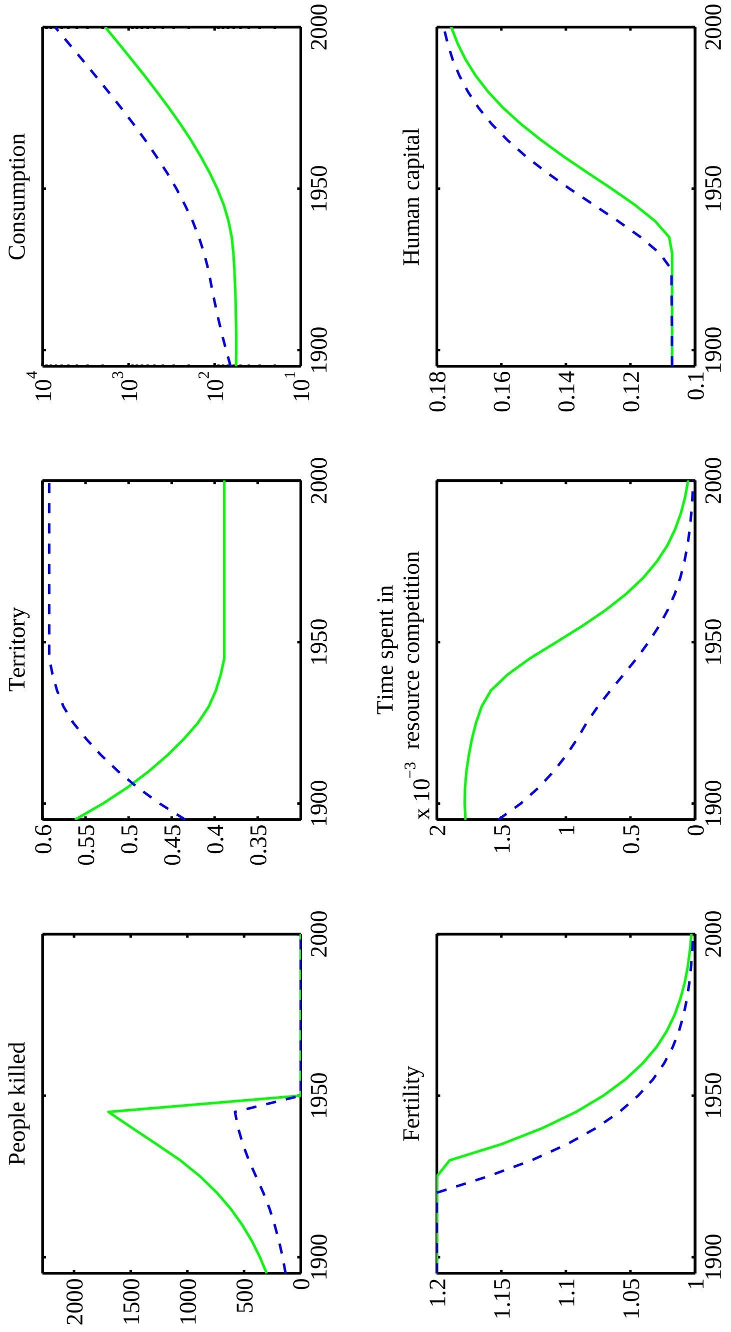

Figure 5: Simulation results in the extended model