Modernization, Climate Variability and Vulnerability to Famine

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Abstract

This paper shows that under climate variability the transformation from a rural to an incomplete market economy can increase the vulnerability of peasants to famine. This can occur even if improvements in technology have raised agricultural productivity and made production less responsive to environmental shocks. This paper helps explain the catastrophic effects produced by widespread droughts in large areas of tropical regions during the second half of the 19th century. Indeed, the results of the model largely confirm Karl Polany's view that the millions of fatalities of that period resulted from the introduction of market mechanisms by colonial institutions, which lowered the ability of agricultural societies to keep food stocks from good seasons to compensate for poor harvest of others. Although the introduction of new modes of production and the modernization of infrastructures imply a greater stability of wages, capitalist decisions can easily increase the risk of famine. Indeed, negative environmental shocks can produce a drop in wages that outweighs the increase in wages due to an equivalent positive environmental shock. Consequently, the level of the stocks increases more slowly in good seasons than it decreases in bad ones. Such an asymmetry crucially depends on the degree of labour market competition between capitalists: the higher their market power, the more likely it is that this institutional change has negative effects on vulnerability.

JEL classification: Q18; N50; O13; C61; J10
Keywords: Climate Variability; Feast-Famine Cycles; Population Dynamics; Subsistence Consumption; Colonialism.

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1 Introduction

Within the extensive literature on the engine of economic development, there is a lack of analyses on the evolutionary impact of climate variability.[1]

Underestimation of this element is not common in other social sciences. In the last few decades, for example, archaeologists and anthropologists have shown that climate variability affects the reproductive choices of individuals, causing major development of localized cultural investment (Dunnell, 1999). Such theories suggest that different degrees of climate variability across places and time can lead to the emergence of different strategies for adjustment. Indeed, in order to combat feast-famine cycles, in places with severe climate variability – like tropical regions affected by ENSO[2] – people develop the habit of keeping stocks of agricultural supplies to maintain a balance between good and bad seasons.

Any balance which results from an evolutionary process of adaptation to local environmental conditions may be harmed by sudden changes in the institutional setting, inducing higher vulnerability of population to dramatic events like famines. This hypothesis is supported by historical evidence from India and other tropical regions in the second half of the 19th century, as colonialism induced a major change in traditional institutions through the development of a *market economy*. During that period, India suffered 24 intense famines which caused 20 million deaths (as per official records).[3] Digby (1901) noted that “stated roughly, famines and scarcities were four times as numerous, during the last thirty years of the 19th century as they were one hundred years ago, and four times as widespread”. Those negative

[1] By climate variability we mean changes in weather between one season and the next which may cause great variations in agricultural yields. Although the impact of yearly variations has not yet been studied in depth, some have investigated the evolutionary impact of climate variation using averages for centuries/millennia. For example Bowles and Choi (2002) analyze the importance of this kind of climate change for the emergence of agricultural societies.

[2] ENSO (El Niño-Southern Oscillation) is a set of interacting parts of a single global system of ocean-atmosphere climate fluctuations that come about as a consequence of oceanic and atmospheric circulation.

[3] Davis (2001, tab 0.1) presents estimates of the millions of fatalities caused in India by two droughts: 1876-79 and 1896-1902. Estimates vary from 12 to 29 million deaths. According to Walford (1878, 434-442) there were 31 serious famines in 120 years of British rule compared to 17 in the 2000 years before British rule.

shocks affected the Indian macroeconomic performance. Although historians disagree on per capita income data, most estimate a zero or negative rate of growth.[4] At the same time, life expectancy fell by about 20%[5]

The severe climate conditions of that period – what Nature in 1878 called "the most destructive drought the world has ever known"[6]– cannot be seen as the only explanatory factor for famines: institutional failure certainly played a role. Indeed, when El Niño hit the plains of North China in 1743-1744 – an event which is comparable in severity to the Indian drought in 1876-79 – institutions were instead crucial in keeping the population from starving. In that instance, the Qing Empire managed to feed two million peasants for eight months by using subsistence goods stored by the imperial authority (Will, 1990; Whetton and Rutherfurd, 1994).

The literature on the causes of famines has gradually recognized the relevance of social and economic regimes. Traditional explanations were mainly based on the link between a decline in food availability and the Malthusian population law.[7] However, food availability proved an incomplete explanatory variable, since many famines were associated to small reductions in aggregate food grains production. For instance, in the Bengal famine of 1943 – defined by Sen (1977) as a *boom famine* – there was no crop failure. Moreover, according to Famine Commission (1880, 1898), during the second half of the 19th century in India there was always a positive surplus in food grain production. This estimate is supported by the fact that India continued to be a net exporter of food grains in all famine periods. A new strand of literature on famines originated from Sen's contribution (Sen, 1981a,b; Drèze and Sen, 1989), which "analyzes famines as economic disasters, not as just food crises" (Sen, 1981a, p. 459).[8] Entitlement theories clarify that

[4]See for instance Hyndman (1919); Davis (1951); Habib (1985); Roy (2002). In particular Hyndman (1919) estimates a reduction of 30% in the second half of the 19th century.

[5]Habib (1985, p.373) shows on the basis of decennial censuses that the male average life expectancy at birth decreased from 23.67 years in 1870s to 19.42 in 1910s. Moreover McAlpin (1983) presents rates of population growth in five different zones. While the average annual rate of growth from 1872 until 1921 was 0.37 percent, most of the zones presented negative rates of growth during the decade 1891-1901.

[6]*Nature*, 1878, p.404

[7]For a survey on the decline in food availability see for instance Osmani (1996).

[8]Sen's entitlement theory attracted the interest of many economists investigating the causes of famines. See for instance Mitra (1982); Srinivasan (1983); Ravallion (1987, 1997).

famines arise from two simultaneous components: the contraction of endowments and the worsening of exchange relations for net buyers of food.

Ghose (1982) for example analyses Indian famines from 1860 to 1910. He points out that India's agrarian economy at that time was "only partially monetised" (Ghose, 1982, p. 377) since laborers were generally paid in kind, and that relative payments of food and non-food producers remained quite stable over the period. Hence, famines were not caused by a change in relative prices but were related to the "employment entitlements" of non-food producers; indeed, crop failure might reduce the demand of food producers for artifacts and other services, implying the consequent loss of employment entitlements by non-food producing rural families.[9]

Our study belongs to the approach of entitlement theories, but analyses the change in food-stock entitlements that occurred due to the institutional change in India in the second half of the 19th century. Polanyi (1944) asserts that the origins of famines in India in that period are tied to the introduction of the free market mechanism for the provision of subsistence goods, which substituted and demolished the village community.

> Failure of crops was, of course, part of the picture, but dispatch of grain by rail made possible to send relief to the threatened areas; the trouble was that people were unable to buy corn at rocketing prices, which on a free but incompletely organized market were bound to be a reaction to a shortage. In former times small local stores had been held against harvest failure, but these had been now discounted or swept away into the big market.(Polanyi, 1944, p.160)

In other words, speculations and rocketing prices of subsistence goods during crises are symptoms – not causes – of the inability of rural families to obtain their necessities, due to the reduction in local food stocks. Polanyi's argument raises two important questions: i) why did the expansion of market economy induce a strong reduction in local food stocks? ii) Why did the market mechanism not provide reliable alternative safety tools for times of negative climate shocks?

The market economy had great potential to bring greater wage stability

[9]Critiques of this approach point out that various difficulties arise in applying entitlement theory to rural areas where property rights are not individually established (Devereux, 2001). Common property and open access regimes and other rules and norms which govern access to natural resources – like the *Jajmani* system in northern India (Commander, 1983) – are typical social arrangements in famine-prone societies.

thanks to market and infrastructure modernization. The strength of modernization was significant in India: the railway system, which had a network of 6400 km in 1870, had been expanded to 61220 km in 1920; at the same time, the irrigated area increased from 1.05 million acres in 1871 to 3.4 in 1921. In the late 1930s, one acre in six was irrigated thanks to government schemes.[10] Such a great effort modified the structure of the labour market and changed the traditional mechanisms for the determination of real wages. This change, though, did not diminish the vulnerability of peasants to climate shock, and resulted instead in severe famines and massive fatalities. Our paper provides a theoretical explanation of this puzzle.

We model a *mixed economy* with a modern and a traditional sector and we compare it with a simplified traditional society. Our analysis points out that in the mixed economy the higher the power of firms in the labour market, the higher the likelihood that the vulnerability of peasants to famine will increase. The substitution of market mechanisms for traditional social and economic institutions can have negative consequences in an environment characterized by strong climate variability. In that case, negative environmental shocks produce a drop in wages that outweighs the increase in wage due to an equivalent positive environmental shock. Consequently, the level of stocks increases more slowly in good seasons than it decreases in bad ones. Such asymmetry in the long run can reduce the ability to keep adequate food stocks even if wages are more stable, thereby increasing the vulnerability of peasants to famine.

The rest of the paper is organized as follows: section 2 presents the theoretical model underlying the traditional economy; section 3 explores the effect of the introduction of a modern sector on the relationship between wages and climate variability; section 4 compares the population dynamics in the two economies through simulations; section 5 concludes with some final remarks.

[10] For a detailed historical investigation on the impact of the irrigation system on Indian performance see Stone (1984).

2 The Basic Model of a Traditional Economy

We aggregate the whole productive structure of the economy into a single sector which produces subsistence for the whole community. Assuming a Cobb-Douglas production function with constant returns to scale, the production of food grain C in period t is given by

$$C_t = \lambda_t L_t^{\delta} T^{1-\delta}, \tag{1}$$

where L_t is the population level, T is the amount of available land, $\delta \in (0, 1)$, and λ_t is an index of the land fertility which depends on the climate of period t. For simplicity, we assume that

$$\lambda_t = \Lambda(1 + \omega_t), \tag{2}$$

where Λ is the average land fertility, and $\omega_t \in (-1, 1)$ is the variability associated to the weather, which expresses the percentage variation in fertility around the average. This term is assumed a zero-mean white noise which may be represented by a transformation of the normal distribution.[11] The amount of land is fixed and can be normalized to one. Hence the total product in each period can be expressed as

$$C_t = \Lambda(1 + \omega_t) L_t^{\delta}. \tag{3}$$

Since land is a common good and the whole population contributes to production, each individual gets the average product, that is

$$c_t = \Lambda(1 + \omega_t) L_t^{\delta-1}. \tag{4}$$

Note that since the marginal productivity of labour is decreasing ($\delta < 1$), the average product diminishes as the population increases. We assume that there exists a level of subsistence $\bar{c}$ necessary for the survival of individuals. Since the environment is characterized by strong variability, at times the level of the average product can be less than its subsistence level. Obviously, the greater the population level the more likely it is that $c_t < \bar{c}$. In order to reduce the variability in the population level, societies stock part of the

[11] In the simulations, this transformation is given by $\omega_t = (1 - e^{x_t})/(1 + e^{x_t})$, where $x_t \sim N(0, 1)$.

product in the good seasons, and use it in bad seasons in order to combat famine cycles. In order to minimize the risk of famine, we assume that in any period each individual consumes $\bar{c}$ for surviving and stocks all the remaining product up to a certain level of the stock $\bar{s}$. Hence, for the whole community the maximum level of food stock $\bar{S}$ is proportional to the population level, that is

$$\bar{S}_t = \bar{s}L_t. \tag{5}$$

When this maximum level of food stock is reached and the seasonal production generates a surplus again, the remaining resources are employed for reproduction, and the population increases. Therefore, the wage dynamics determines the evolution of both population and food stocks. Then it holds:

$$\begin{aligned} &if \;\; c_t \geq \bar{c} \Longrightarrow \begin{cases} S_{t+1} = & S_t + \min\{(c_t - \bar{c})L_t, \bar{S}_t - S_t\}, \\ L_{t+1} = & L_t + \phi\left[(c_t - \bar{c})L_t - (S_{t+1} - S_t)\right] \end{cases} \\ &if \;\; c_t < \bar{c} \Longrightarrow \begin{cases} S_{t+1} = & S_t + \max\{(c_t - \bar{c})L_t, -S_t\}, \\ L_{t+1} = & L_t + \phi\left[(c_t - \bar{c})L_t - (S_{t+1} - S_t)\right] \end{cases} \end{aligned} \tag{6}$$

where ϕ is the fertility parameter.

Proposition 2.1

In the long run the population spends most of the time around the equilibrium level $L^* = (\frac{\Lambda}{\bar{c}})^{\frac{1}{1-\delta}}$*; the expected level of average product is* $E(c_t) = \bar{c}$ *and then* $E(\Delta S) = 0$.

Proof

See Appendix A.

The intuition is extremely simple. When the population level is low, the average product of individuals is greater than $\bar{c}$ also for low levels of land fertility λ_t (i.e. in bad seasons), and the level of the food stock on average will increase up to $\bar{S}$. At that point, any additional resource is spent on reproduction and the population will increase, approaching the level L^*. This long-run equilibrium, obtained from the representation of an ideally egalitarian society, is also consistent with the feudal pre-colonial society described by Scott (1977) in which few landowners guaranteed that enough stocks were kept to provide subsistence to all their tenants and workers.

3 Mixed Economy

3.1 The productive structure

Our attempt aims to model the change from a traditional to a market economy in order to evaluate the real effects of the introduction of intensive production on the vulnerability of peasants. We consider that capitalists keep a considerable part of the available land for food grain production by using a new technology. The total product is partly used to pay the workers while the rest is sold abroad on the international market. While colonialists have access to the world economy, workers consume only the local agricultural good.[12] Production is managed by n capitalists who employ part of the labour force. The rest of the population continues to produce subsistence in the remaining land, guaranteeing full employment.

Given this setting, the new economy is characterized by two sectors, one showing the same properties as the traditional society, the second driven by capitalists' decisions. We call this economy *mixed*. Competition and mobility of workers imply wage equalization in the two sectors. This means that the wage level is determined in the traditional sector according to the average-product rule, and is affected by climate shocks. Capitalists in each period maximize their profits by choosing the level of employment in plantations (L_E), taking into account the fact that this decision influences the quantity of labour which remains in the traditional sector (L_C), which in turn influences the current wage of the whole economy.

In every period, food production in the remaining traditional sector is given by:

$$C_t = \lambda_t (1-q)^{1-\delta} {L_C}_t^{\delta}. \tag{7}$$

This function is the same as before, the only changes being that the available land is $(1-q)$ and the number of workers is L_C. In every period, each firm i produces the agricultural good with the same technology, according to the

[12] The assumption of an economy with a single good avoids any effect of shifts in exchange entitlements and allows us to focus only on the changes in real wage caused by the new productive structure. Moreover, note that we are analyzing a late 19th century agricultural economy where workers were usually paid in kind (Ghose, 1982).

following production function:

$$E_{it} = \alpha {q_i}^{1-\delta} {L_{Eit}}^{\delta}, \quad \forall i = 1 \dots n;^{13} \tag{8}$$

where E_i, q_i and L_{Ei} are respectively the output, the amount of land and the employed labour of firm i. Obviously, $\sum_{i=1}^{n} E_i = E$, $\sum_{i=1}^{n} q_i = q$, and $\sum_{i=1}^{n} L_{Ei} = L_E$. For simplicity's sake, we consider that the total amount of land appropriated by capitalists (q) is given by political factors (i.e. it is determined exogenously), and that each capitalist has the same share of land, hence $q_i = q/n$. This last assumption allows us to consider n an index of market power. Unlike the traditional sector, thanks to investment in the modern sector, α does not depend on climate variability.[14] In addition, since all the population which is not employed in sector E works in sector C,

$$L_{Ct} = L_t - L_{Et}. \tag{9}$$

The average product (c) is equal to the wage (w) in the modern sector, so

$$w_t = c_t = \lambda_t (1-q)^{1-\delta} (L_t - L_{Et})^{\delta-1}. \tag{10}$$

Hence the profits of each firm i are

$$\Pi_{it} = E_{it} - w_t L_{Eit}, \quad \forall i = 1 \dots n. \tag{11}$$

Note that profits are expressed in terms of food grain. The fact that the production share in the hands of capitalists is sold abroad at a certain international price, does not change the capitalists' decisional process.[15]

From equations (8) and (10) and (11), we get

$$\Pi_{it} = \alpha \left(\frac{q}{n}\right)^{1-\delta} L_{Eit}^{\delta} - \lambda_t (1-q)^{1-\delta} (L_t - L_{Et})^{\delta-1} L_{Eit}, \quad \forall i = 1 \dots n. \tag{12}$$

Capitalists maximize their profits with respect to the number of workers in their firm L_{Ei}.

[13] In order to simplify the analysis it is assumed that the exponent of the production functions are the same in the traditional and modern sectors. In a previous version of the paper, two different parameters were considered; this change would complicate the model adding very little.

[14] For our results, it is sufficient to assume that land fertility α is less responsive to climate variability than λ since only the ratio between these two variables matters.

[15] We are not considering the case in which the change in the international price makes it worth producing a different agricultural good in the plantations.

Proposition 3.1 *The only Nash equilibrium is the symmetric equilibrium. Therefore setting $L_{Ei} = L_E/n$, the optimal level of workers employed in the plantations must satisfy the following condition*

$$\frac{\alpha\delta}{\lambda_t}\left(\frac{q}{1-q}\right)^{1-\delta} = \frac{L_{Et}^{1-\delta}[n(L_t - L_{Et}) + (1-\delta)L_{Et}]}{n(L_t - L_{Et})^{2-\delta}}. \tag{13}$$

Proof

See Appendix A.

From equations (10) and (13), the wage level at equilibrium is

$$w^* = \frac{n(L - L_E)}{n(L - L_E) + (1-\delta)L_E}\alpha\delta q^{1-\delta}L_E^{\delta-1}, \tag{14}$$

and the total profits are

$$\Pi^* = \frac{(1-\delta)[n(L - L_E) + L_E]}{n(L - L_E) + (1-\delta)L_E}\alpha q^{1-\delta}L_E^{\delta}, \tag{15}$$

where, $\alpha q^{1-\delta}L_E^{\delta}$ is the total product, and the other member is the unit profit. This amount measures the market power of the capitalist sector: when n decreases, this expression increases, meaning that the reduction in the number of firms increases the quota of production in the hands of capitalists. Moreover, in the case of monopsony, i.e. $n = 1$, we have the maximum level of unit profits and then the highest market power, while when n goes to infinity we obtain the usual results of perfect competition and the market power is zero.

Given equation (13), it is not possible to obtain an explicit function for $L_E(L, \lambda, t)$. However, the Implicit Differentiation Theorem can be used in order to obtain the functional form of the partial derivatives and hence the sign of the variations in the optimal level L_E^*.

3.2 Climate Variability and Wages

Analysis of the traditional economy clarified that the population dynamics is driven by changes in the wage level which determines the reduction or accumulation of the stocks of subsistence. In this case instead, variations in wages are driven not only by climate variability but also by capitalists' decisions. Workers' preferences and their consumption patterns are the same as those presented for the traditional economy. Hence, thanks to the storing process, variations in the population level are more slower than climate variations and changes in the allocation of labour between the two sectors. For this reason in this section we analyse the relation between climate variability and wages given a fixed population level.

Appendix A shows that the optimal level of labour in a plantation is a decreasing function of soil fertility – i.e. $\frac{\partial L_E^*}{\partial \lambda} < 0$. This means that when soil fertility increases thanks to a favourable season, $(\lambda_t > \Lambda)$, capitalists benefit from reducing the amount of labour in order to compensate for the increase in wage driven by the increase in the average product in the traditional sector. Hence, in good seasons, the wage of the economy is less than the average product in the traditional society and peasants can store a smaller amount of the subsistence good. However, when climate variability is negative, capitalists increase the amount of labour employed in plantations, inducing a wage level exceeding that obtained in the traditional society. Therefore, thanks to the improvement in technology, profit maximization in the modern sector induces greater stability of peasants wages in the mixed economy with respect to the traditional one, everything else being equal.

Nevertheless, this process is not neutral in terms of the vulnerability of peasants to famine. The overall effect can be shown by taking the derivative of wage (10) with respect to λ, i.e. $\frac{\mathrm{d}w}{\mathrm{d}\lambda}$.[16] As we would expect, this derivative is positive and lower than the same derivative in the traditional economy. However, the derivative is no longer constant.[17]

Proposition 3.2

Let us define $x \equiv L_E/L$ the quota of workers employed in the capitalist sector. Then it holds that

$$\frac{\mathrm{d}^2 w}{\mathrm{d}\lambda^2} \leq 0 \Longleftrightarrow n \leq n^* \equiv \frac{(2-\delta)(\delta x + 1 - \delta)x}{\delta(1-x)^2}, \tag{16}$$

Proof

See Appendix A.

[16]Appendix A provides calculation details.

[17]In the pre-colonial society, by contrast, this derivative does not depend on λ, $\frac{\mathrm{d}w}{\mathrm{d}\lambda} = L_t^{\delta-1}$, see equation (4).

When the number of firms is lower than n^*, Proposition 3.2 implies that $\frac{d^2 w}{d\lambda^2} < 0$. In this case, the variation in wage is higher (lower) for low (high) values of λ. This means that wage variability in the mixed economy is higher in bad seasons than in good ones. In other terms, when $\frac{d^2 w}{d\lambda^2} < 0$, negative environmental shocks produce a drop in wages that outweighs the increase in wage due to an equivalent positive environmental shock. Two remarks should be made on the nature of this result. First, the higher the share of workers employed in plantations, i.e. x, the more likely the vulnerability of peasants increases. Indeed, the derivative of the last term of (16) with respect to x is positive. The increase in the share of workers employed in the modern sector may depend on an increase in the share of land employed in modern production, i.e. on an expansion of the market economy and on the consequent marginalization of the traditional sector.

Secondly, the number of firms plays a crucial role. In equilibrium, a higher degree of competition between capitalists reduces the risk of an increase in the vulnerability of peasants to famine after the introduction of the capitalist sector. The intuition can be deduced from equations (14) and (15). Indeed, as we pointed out above, there is a direct relation between the share of production in the hands of workers and the number of firms. In the case of very few firms, their market power is relatively high, and this power through the maximization of profits has negative consequence on the capability of peasants to store subsistence goods.

Figure 1 clarifies this result. The thinner curve drawn in the graph represents the locus in which the second derivative of wage with respect to λ is equal to zero as in the traditional economy. Above this curve the introduction of plantations in an environment affected by climate variability induces increases in vulnerability, while below the curve the vulnerability decreases. Whether the economy lies above or below the curve depends on other model parameters, i.e. the ratio α/Λ and q. The bold curve represents the optimal level of employment in the plantations given by equation (13). In this example when the number of firms is higher than about 20, the second derivative of wage with respect to λ becomes positive.

However, in the framework of this model we are considering an agricultural economy where the plantations which are introduced encounter a local

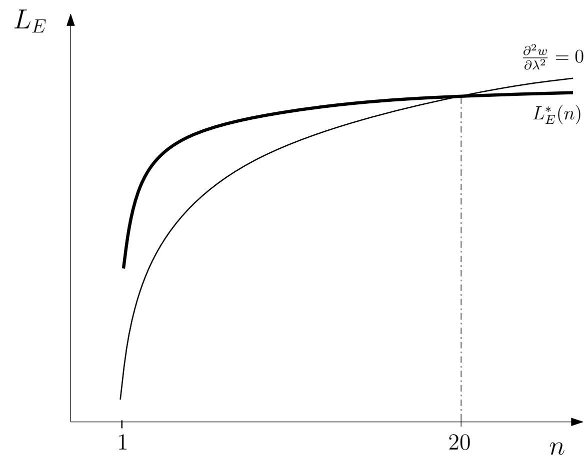

Figure 1: Climate Variability and Wages. Values of parameters: $\delta = 0.7$, $\alpha = 3.5$, $\lambda = 2$, $q = 0.65$.

labour market. Thus we expect the labour market to consist of workers who reach the plantation on foot. In this case, the number of firms must be very low. Under these hypotheses, the model predicts that the introduction of plantations has negative consequences on the vulnerability of people to famine, despite the fact that the economy as a whole is richer than before thanks to the higher productivity of the new technology.[18] This result is consistent with the evidence that India continued to be a net exporter of food grains in all famine periods in the late 19th century.

4 Traditional versus Mixed Economy

4.1 Labour Intensity

Once capitalists have chosen the optimal level of employment in plantations, the wage of the whole economy, i.e. equation (10), is determined. Consequently, the dynamics of both, subsistence stock and population are determined by the system (6). Hence, we can deduce an important result.

[18]In the simulation provided in Figure 1, the number of firms required to avoid the increase in vulnerability is about 20. Note also that if the marginalization of the traditional sector increases, i.e. q increases, only the marked line would shift upwards: therefore the intercept would significantly move to the right.

Proposition 4.1

In the absence of climate variability, the equilibrium population level L^* is given by the solution of following equation:

$$\frac{\alpha\delta}{\Lambda}\left(\frac{q}{1-q}\right)^{1-\delta} = \frac{\bar{L}_E^{1-\delta}[n(L-\bar{L}_E)+(1-\delta)\bar{L}_E]}{n(L-\bar{L}_E)^{2-\delta}}, \tag{17}$$

where $\bar{L}_E = (\frac{\Lambda}{\bar{c}})^{\frac{1}{1-\delta}} q$

Proof see appendix A.

This means that in a static environment, if at the beginning of the transition to colonialism the population level is equal to the equilibrium level of the traditional economy, the profit maximization in the capitalist sector induces a decrease (increase) in the population level if $L_E < \bar{L}_E$ ($L_E > \bar{L}_E$). The final result depends on the intensity of labour per unit of land in the capitalist sector.

More precisely, Appendix A shows that in order to obtain the same long-run equilibrium on the level of population before and after the introduction of the modern sector, the number of firms n must be equal to $\bar{n}$, where

$$\bar{n} \equiv \frac{\Lambda(1-\delta)q}{(\alpha\delta-\Lambda)(1-q)}. \tag{18}$$

If the number of firms is greater (lower) than $\bar{n}$, without climate variability the population would increase (decrease). However, as we will show in the next section, the presence of climate variability can induce a reduction in the population in the long-run even when $n > \bar{n}$.

4.2 Feast-Famine Cycles

In order to clarify the importance of asymmetry in the wage-climate variability relation, Figure 2 presents a comparison between the population level in the two economies subject to the same variation in climate trend. In order to facilitate the comparison the parameters Λ, δ, α, q and n are such that equation (18) holds. This means that the two economies would show the same population level, ($L^* = 10000$ in the example) under a static environment. Instead, under climate variability, the two economies evidence different long-term dynamics in population level. While the traditional economy hovers around the equilibrium level L^* characterized by a series of relatively modest feast-famine cycles, the mixed economy is subject to a long-term reduction in the population level far from the equilibrium level under a static environment, L^*.

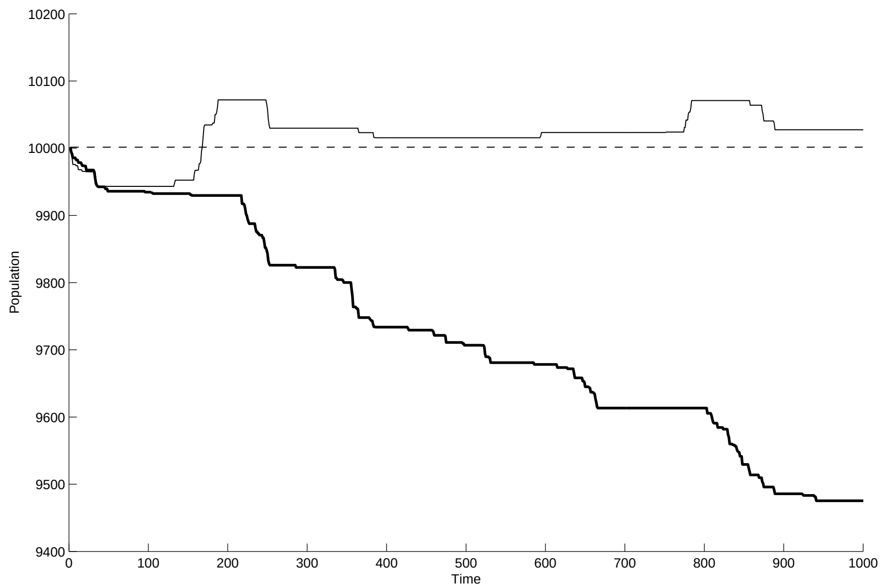

Figure 2: Mixed versus Traditional Economy. The horizontal dashed line indicates the population level in the two economies without climate variability. The thinner and the bold paths show the population level in the traditional and in the mixed economy subject to the same climate variability. Parameters: $\Lambda = 2$, $\delta = 0.75$, $\alpha = 3$, $q = 0.8$, $\bar{C} = 0.2$, $n = 8$, $\phi = 0.01$, $\bar{s} = 1.6$, $t = 10000$. Initial conditions $L(0) = 1000$ and $S(0) = 0$.

If the number of firms increases, the difference between the two economies in the severity of feast-famine cycles diminishes. In Figure 3, we replicate the same simulation as before, but consider a higher number of firms ($n = 10$). Interestingly, in this case the population of the mixed economy would increase without climate variability, meaning that part of the benefit of modern technology would be appropriated by peasants. Nevertheless, when climate shocks are considered, peasants face a higher vulnerability to famine in the mixed economy than in the traditional one. Moreover, also in this case, simulation predicts a series of famine cycles.

The impact of the introduction of the modern sector on famine is striking.

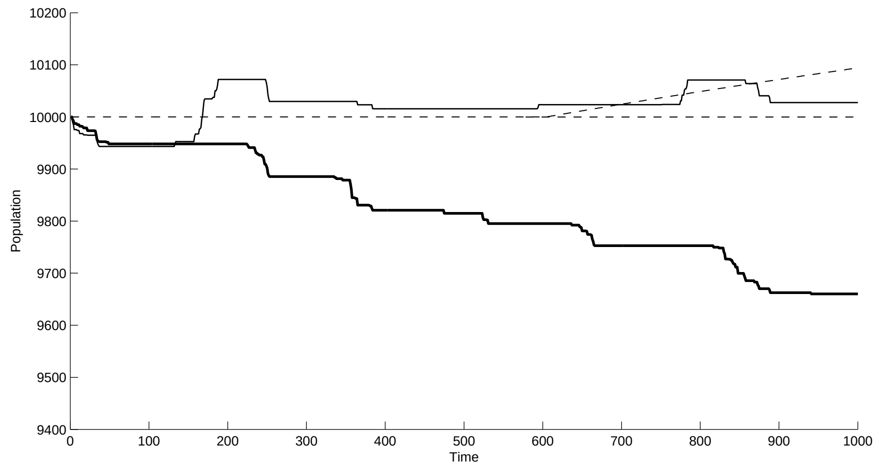

Figure 3: Mixed versus Traditional Economy. The horizontal dashed line and the increasing curve indicate the population level without climate variability in the traditional and in the mixed economy, respectively. The thinner and the bold paths show the population level in the traditional and in the mixed economy subject to the same climate variability. Parameters: $\Lambda = 2$, $\delta = 0.75$, $\alpha = 3$, $q = 0.8$, $\bar{C} = 0.2$, $n = 10$, $\phi = 0.01$, $\bar{s} = 1.6$, $t = 10000$. Initial conditions $L(0) = 1000$ and $S(0) = 0$.

Note that this process produces divergent dynamics after a few years. This means that the presence of a capitalist sector may induce an impoverishment of the whole economy even if, thanks to better technology, the total product could increase, and capitalists could continue to export food grain during famines. In order to reduce the vulnerability of peasants to famine a larger number of firms is required. Indeed, a high degree of competition would reduce the asymmetry between the wage variation in good and bad seasons.

Appendix A, presenting a long-term simulation, shows that in the absence of additional institutional changes the population in the mixed economy would tend to move around a new equilibrium level, which is significantly lower than the traditional one. Indeed, when the population decreases, there is a gain in productivity in the traditional sector due to the decreasing returns to scale with respect to labour. Analysis of the properties of this new long-term equilibrium goes beyond the goal of this work. We leave the development of this point to future research.

5 Concluding Remarks

This paper models the transition from a traditional to a colonial economy in an environment characterized by strong climate variability. The analysis attempts to provide a formal description of the reasons why, after the introduction of some elements of market economy, famine cycles hit India – and other tropical regions – in the late 19th century.

We present a very simplified traditional economy where climate variability affects food production in every period. In order to reduce the amplitude of feast-famine cycles, societies develop the habit of keeping stocks of subsistence goods. This assumption fits the evidence of high levels of stocks that have been found in many traditional economies. Under colonialism, the introduction of a new agricultural sector managed by capitalists changed the allocation of labour on the available land. The maximization of profits in the capitalist sector has the positive effect of reducing wage variability thanks to new technologies and infrastructure modernization. Nevertheless, capitalist production can easily produce a negative asymmetry between stocks of subsistence saved in good and in bad seasons. Indeed, negative environmental shocks produce a drop in wages that is larger in magnitude than the increase in wage due to an equivalent positive environmental shock. In the long run, this dynamic increases the vulnerability of peasants to famine.

The power of firms on the labour market determines whether the institutional changes have positive or negative consequences on the vulnerability of peasants to famine. In our framework this market power is measured by the number of firms which operate in the same sector. We found that there is a threshold number of firms below which the risk of famine increases, while a reduction in vulnerability is associated above that threshold. This suggests that a higher degree of competition in the capitalist sector may reduced the risk of famine. However, in the late 19th century, the modern sector was accounted for mainly by the production of intensive plantations. Such firms could control a local labour market with very high market power. Moreover, we show that, *ceteris paribus*, the greater the marginalization of the traditional economy, the more likely it is that the introduction of this modern sector increases the risk of famine.

By comparing the evolution of a traditional and a mixed economy which would have the same long-term population level under a constant environment, we obtain through simulations the outcome that under the same variation in climate trend the two economies show divergent long-term dynamics. While the traditional economy moves around the average population level, the mixed economy encounters a series of famine cycles which lead the population far from its equilibrium level without climate variability.

A Appendixes

Proof of Proposition 2.1

When $c_t = \bar{c}$ then $L_t = \left[\frac{\Lambda(1+\omega_t)}{\bar{c}}\right]^{1/1-\delta}$. If $\omega_t = 0$ we get $L_t^* = \left(\frac{\Lambda}{\bar{c}}\right)^{1/1-\delta}$. Given equation (4) and the properties of ω_t, $E(c_t) = \Lambda L_t^{\delta-1}$. This implies that if $L_t < L_t^*$, the expected level of the average product is greater than the subsistence level of consumption, i.e. $E(c_t) > \bar{c}$. Hence, on average the population accumulates stocks of subsistence reaching the level $\bar{S}$ in finite time since the average surplus does not change for a given population level. This result holds for any level of $L_t < L_t^*$, while the reverse applies in the opposite case. Therefore the population in the long run remains close to the equilibrium level L_E^*.

Proof of Proposition 3.1

From equation (12), the maximization of profits – $\frac{\partial \Pi_i}{\partial L_{Ei}} = 0$ – gives the following result:[19]

$$\frac{\alpha\delta}{\lambda}\left[\frac{q}{n(1-q)}\right]^{1-\delta} = \frac{[L - L_{E-i} + \delta L_{Ei}]L_{Ei}^{1-\delta}}{(L - L_{E-i} - L_{Ei})^{2-\delta}}. \tag{19}$$

This expression is the reaction function of firm i, meaning that, given any level of λ and L, for any aggregate level of the employment of the other $n-1$ firms, L_{E-i}, capitalist i selects the optimal level of employment L_{Ei}^*. Assuming a symmetric equilibrium, i.e. $L_{Ei} = L_E/n \forall i$ we get equation (13).

Existence. Since the value of the LHS of (13) is positive, the RHS of (13) is continuous in L_E, the value of the RHS of (13) for $L_E = 0$ is zero, and the derivative of the RHS of (13) with respect to L_E is always positive; then there exists one and only one level of L_E such that equation (13) is satisfied.

The symmetric equilibrium is a Nash equilibrium. Let us consider that $n-1$ firms have employed L_E/n workers, then $L_{Ei} = L_E/n$ is a Nash equilibrium if and only if the best response for firm i is to employ $L_{Ei} = L_E/n$ workers. The first order condition when $L_{E-i} = \frac{n-1}{n}L_E$ can be written as

$$\frac{\alpha\delta}{\lambda}\left(\frac{q}{1-q}\right)^{1-\delta} = \frac{\left[(1-\delta)L_{Ei} + L - \frac{n-1}{n}L_E - L_{Ei}\right]L_{Ei}^{1-\delta}n^{1-\delta}}{(L - \frac{n-1}{n}L_E - L_{Ei})^{2-\delta}}. \tag{20}$$

Note that the LHS of equation (20) is equal to the LHS of (13) and that the derivative of the RHS of equation (20) with respect to L_{Ei} is always positive. Taking into account the result of *Existence*, this implies that there exists one and only one optimal solution

[19] We drop the time variable for convenience.

for firm i which must be $L_{Ei} = L_E/n$. Therefore the symmetric equilibrium is a Nash equilibrium.

Uniqueness of the Nash equilibrium. Let us consider the derivative of RHS of equation (19) with respect to L_{Ei} and L_{E-i}. Both the signs are positive. This result implies that if firm i is at equilibrium – i.e. is maximizing its profits – and the number of workers employed in the modern sector by the rest of the firms increases, then the optimal choice for i would be to reduce its level of employment L_{Ei}.

Let us assume that $L_{E-i} > \frac{n-1}{n}L_E$. Since the only variable which matters for firm i is the level of employment of the rest of the firms, it holds that firm i would employ L_E/n workers when $L_{E-i} = \frac{n-1}{n}L_E$, independently of the distribution of employment between the other $n-1$ firms. Hence, for $L_{E-i} > \frac{n-1}{n}L_E$, all the firms employing $L_{Ei} > L_E/n$ find it better to reduce the employment below L_E/n. The same applies in the opposite case.

Therefore, the only Nash equilibrium is the symmetric equilibrium.

Allocation of labour and wages

The Implicit Differentiation Theorem can be used to analyse the effect of climate variability – changes in λ – on the optimal level of employment in the plantations – L_E^*. Given the level of prices and total population, equation (13) can be written as

$$F(\lambda, L_E) = \frac{{L_E}_t^{1-\delta}[n(L_t - L_{Et}) + (1-\delta)L_{Et}]}{n(L_t - L_{Et})^{2-\delta}} - \frac{\alpha\delta}{\lambda_t}\left(\frac{q}{1-q}\right)^{1-\delta} = 0. \tag{21}$$

By applying the chain rule, it holds that

$$\frac{\partial F(\cdot)}{\partial \lambda} + \frac{\partial F(\cdot)}{\partial L_E}\frac{dL_E}{d\lambda} = 0, \tag{22}$$

where $F(\cdot) = F(\lambda, L_E)$. Then

$$\frac{dL_E}{d\lambda} = -\frac{\frac{\partial F(\cdot)}{\partial \lambda}}{\frac{\partial F(\cdot)}{\partial L_E}}, \tag{23}$$

The denominator of the RHS is equal to the derivative of the first member of equation (20), which is always positive. Hence

$$\frac{dL_E}{d\lambda} = -\frac{\alpha\delta n q^{1-\delta}}{\lambda^2(1-q)^{1-\delta}}\frac{(L-L_E)^{3-\delta}L_E^{\delta}}{D} < 0. \tag{24}$$

where

$$D \equiv (1-\delta)[(1-\delta)L_E + n(L-L_E)](L-L_E) - (n+\delta-1)(L-L_E)L_E$$
$$+(2-\delta)[(1-\delta)L_E + n(L-L_E)]L_E. \quad (25)$$

Note that $D > 0$. The next step consists in analysing the relation between the current wage level and λ. Given equation (10) we obtain

$$\frac{\partial w}{\partial \lambda} = \left(\frac{1-q}{L-L_E}\right)^{1-\delta} + \frac{\lambda(1-\delta)(1-q)^{1-\delta}}{(L-L_E)^{2-\delta}}\frac{dL_E}{d\lambda}. \quad (26)$$

From equations (13),(24) and (26), we get

$$\frac{\partial w}{\partial \lambda} = \left(\frac{1-q}{L-L_E}\right)^{1-\delta}\left(\frac{N}{D}\right), \quad (27)$$

where

$$N \equiv (1-\delta)[(1-\delta)L_E + n(L-L_E)](L-L_E) - (n+\delta-1)(L-L_E)L_E$$
$$+[(1-\delta)L_E + n(L-L_E)]L_E. \quad (28)$$

Since $N > 0$ we get that $\frac{\partial w}{\partial \lambda} > 0$.

The last step is to obtain the second derivative of w with respect to λ. Note that $\frac{\partial^2 w}{\partial \lambda^2} = \frac{\partial\left(\frac{\partial w}{\partial L_E}\right)}{\partial L_E}\frac{dL_E}{d\lambda}$. Hence, differentiating equation (27) with respect to λ it holds that

$$\frac{\partial^2 w}{\partial \lambda^2} = \left[(1-\delta)ND + (L-L_E)(N'D - D'N)\right]\frac{(1-q)^{1-\delta}(L-L_E)^{\delta-2}}{D^2}\frac{dL_E}{d\lambda}, \quad (29)$$

where, D' and N' are respectively $\frac{\partial D}{\partial L_E}$ and $\frac{\partial N}{\partial L_E}$. Since the second member of the RHS of (29) is positive and $\frac{dL_E}{d\lambda}$ is negative, in order to derive necessary and sufficient conditions on the sign of $\frac{\partial^2 w}{\partial \lambda^2}$, we reduce the analysis to the term in the square brackets. After simplification, it holds that

$$\left[(1-\delta)ND + (L-L_E)(N'D - D'N)\right] \gtreqless 0 \Longleftrightarrow$$
$$\delta(2-\delta)x^2 + (1-\delta)(2-\delta)x - \delta n(1-x)^2 \gtreqless 0, \quad (30)$$

where $x \equiv L_E/L$. It is straightforward to prove that from (30) we get the condition (16). However, Figure 1 shows the function $x(n)$. Solving the second part of condition (30) for x we get $\frac{\partial^2 w}{\partial \lambda^2} < 0$ if and only if $x > x^*$, where

$$x^* \equiv \frac{[2\delta n + (1-\delta)(2-\delta)] - \sqrt{(1-\delta)^2(2-\delta)^2 + 4\delta n(2-\delta)}}{2\delta(n+\delta-2)} \quad (31)$$

Proof of Proposition 4.1

Without climate variability, the population is in equilibrium when the wage level is equal to the subsistence level of consumption. From equations (9) and (10), we get that the number of workers in the traditional sector must satisfy the following equation:

$$\bar{c} = w = \Lambda(1-q)^{1-\delta}(L_C)^{\delta-1}. \tag{32}$$

By solving equation (32), we get $\bar{L}_C = (\frac{\Lambda}{\bar{c}})^{\frac{1}{1-\delta}}(1-q)$ and $\bar{L}_E = (\frac{\Lambda}{\bar{c}})^{\frac{1}{1-\delta}}q$. Hence, the population level is in equilibrium if and only if the optimal level of employment in the modern sector is $L_E^* = \bar{L}_E$. This happens when L is equal to the solution of equation (17).

Equalization of population equilibria under a stable environment

In order to obtain equalization in the average wage level in the two economies, that is $c_t = \bar{c}$ when $L_t = L^*$ and $\lambda_t = \Lambda$ the following system must be satisfied

$$\begin{cases} \frac{\alpha\delta}{\Lambda}\left(\frac{q}{(1-q)}\right)^{1-\delta} = \frac{\left[n\left(L^*-L_E\right)+(1-delta)*L_E\right]L_E^{1-\delta}}{n(L^*-L_E)^{2-\delta}}; \\ \bar{c} = \Lambda(1-q)^{1-\delta}(L^*-L_E)^{\delta-1}; \\ L^* = (\frac{\Lambda}{\bar{c}})^{1/(1-\delta)}; \end{cases} \tag{33}$$

where the first expression is the equation (13) when $\omega_t = 0$, the second implies $w_t = c_t = \bar{c}$, and the third is the equilibrium population level in the traditional economy. Solving the system for n, we get equation (18).

When $n > \bar{n}$ ($n < \bar{n}$) the population in the colonial economy should face an increase (a decrease) for a transitional period.

Long Run Equilibrium

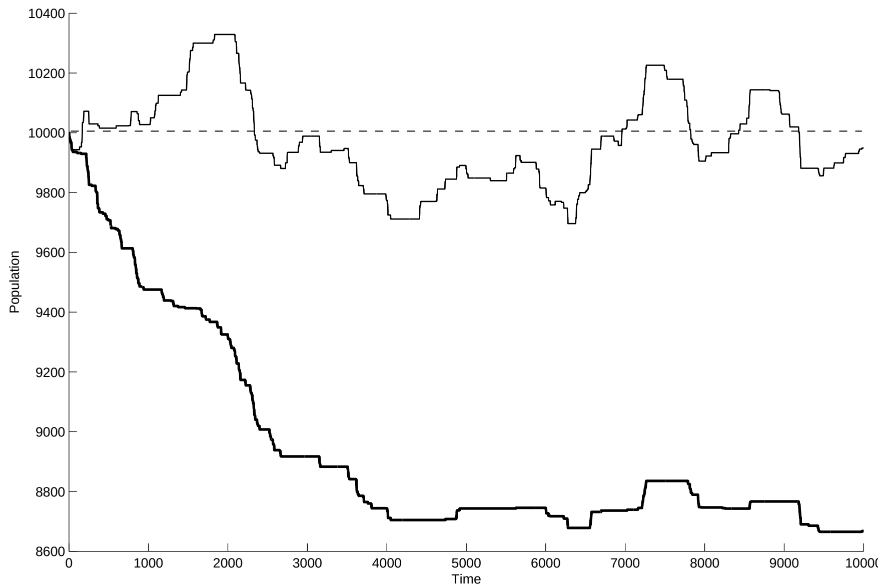

Figure 4: Long Run Dynamics. The horizontal dashed line indicates the population level in the two economies under a stable environment. The thinner and the bold paths show the population level in the traditional and in the mixed economy subject to the same climate variability. Parameters: $\Lambda = 2$, $\delta = 0.75$, $\alpha = 3$, $q = 0.8$, $\bar{C} = 0.2$, $n = 8$, $\phi = 0.01$, $\bar{s} = 1.6$, $t = 10000$. Initial conditions $L(0) = 10000$ and $S(0) = 0$.

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