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MODELING ECONOMIC GROWTH FUELLED BY SCIENCE AND TECHNOLOGY

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MODELING ECONOMIC GROWTH FUELLED BY SCIENCE AND TECHNOLOGY*

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SUMÁRIO

ABSTRACT

This paper suggests a simulation model to investigate how science and technology fuel economic growth. This model is built upon a synthesis of technological capabilities represented by national innovation systems. This paper gathers data of papers and patents for 183 countries between 1999 and 2003, GDP and population for 2003. These data show a strong correlation between science, technology and income. Three simulation exercises are performed. Feeding our algorithm with data for population, patents and scientific papers, we obtain the world income distribution (R=0.99). These results support our conjecture on the role of science and technology as a source of the wealth of nations.

Key-words: simulation models, systems of innovation, economic growth.
JEL Classification: O0

RESUMO

Este artigo propõe um modelo de simulação para investigar a contribuição da ciência e da tecnologia para o crescimento econômico. O ponto de partida são os sistemas nacionais de inovação, um conceito que sintetiza a capacitação tecnológica das nações. Desta forma, o modelo pode preservar simplicidade e parcimônia. Os dados coletados (patentes, artigos e PIB e população, para 183 países) indicam uma forte correlação entre ciência, tecnologia e renda. Três exercícios com simulações são realizados. A correlação entre o mundo simulado e o mundo real é alta (R=0,99), quando o algoritmo é alimentado com dados de população, patentes e artigos científicos.

Palavras-chaves: modelos de simulação, sistemas de inovação, crescimento econômico.
Classificação JEL: O0

1. SCIENCE AND TECHNOLOGY FUELLING ECONOMIC GROWTH

This paper suggests a simulation model to investigate how science and technology fuel economic growth. This model is built upon a synthesis of technological capabilities represented by the concept of national innovation systems, which allows our model to be parsimonious.

What are the theoretical foundations that underline the concept of national systems of innovation? National innovation system (NSI) is a concept that shows how a complex interplay of different actors (firms, universities, public labs, governments, financial institutions etc) pushes the technological development of nations. NSI shows the engine of technological progress at the centre of the process of economic development.

Innovation system is a concept developed by Freeman (1988), Nelson (1988) and Lundvall (1988) in a book that is the first organized presentation of the evolutionist approach as a whole (Dosi et all, 1988). The timing of this presentation is not casual, because for the elaboration of the concept of NSI previous theoretical clarifications were necessary (and it is not casual that NSI is the part V of the book). The first round of this elaboration, at large, took place during the 1970s, with the publication of three pioneering works: Freeman (1974); Rosenberg (1976) and Nelson and Winter (1977). These works involved a lot of theoretical synthesis and dialogue with previous elaboration.[1]

This first round of evolutionary elaboration investigated important subjects as the determinants of technological progress, the role of firms in innovative activities, the microeconomic foundations of evolutionary thinking (rationality, firms behaviour, the combination of routines, search and selection as an alternative to equilibrium etc),[2] a historical account of technological change, including the role of science and its complex interplay with technology, the multifarious actors involved in innovative activities, the role of markets and non-market institutions in innovation, a typology of innovations, indicating the role of imitation and incremental change and the multidimensional changes in the centre of the capitalist system; summarized by Freeman's elaboration on different historical phases of capitalist development.

The result of this first round of theoretical elaboration is the ground work for an explosion of empirical, theoretical and comparative studies using the evolutionary elaboration as reference. Freeman (1994) and Dosi (1997) describe the rich array of subjects worked out by evolutionists after this first round. Among this elaboration, the concept of NSI is presented.

A second round of theoretical elaboration takes place during the 1980s and the 1990s: the concept of NSI is presented (Freeman, 1988, Nelson, 1988 and Lundvall, 1988) and is further developed. Three developments are important and representative. First, Nelson (1993) organizes a comparative study gathering historical and empirical evidences to deepen the understanding of the institutional differentiation between 16 countries (involving developed, catching up and non-developed countries, Argentine and Brazil among them). Second, Lundvall (1992) organizes a book that presents conceptual developments related to the concept of NSI, involving subjects as the role of scientific infrastructure and the financial dimension. Third, Edquist (1997) presents a mix of theoretical issues and empirical topics, contributing to qualify the NSI issue and opening new research

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[1] See Nelson and Winter (1982, pp. 33-45) for a summary of "allies and antecedents of evolutionary theory".

[2] Dosi (1988) presents a broad review of this issue.

subjects related to innovation systems. The NSI as a synthesis of previous elaboration opened new room for further advances in the evolutionary approach in general and for a broadening of the concept of innovation systems.

The third round of evolutionary elaboration on NSIs emphasises new subjects in the research agenda: the connections between NSIs, economic growth and development, convergence and divergence in a global arena. Freeman (1995) is representative of this new round, integrating List's elaboration to connect the NSI framework with development issues. This round coincides with the revival of mainstream economics interest on economic growth during the 1990s. Dosi, Freeman & Fabiani (1994), Fagerberg (1994), and Nelson (1998) are representative of evolutionists' interventions in this debate, benefiting from the rich elaboration of the previous two rounds.

Dosi, Freeman & Fabiani point to a central issue to this paper: how the correlation between technology and GDP increases throughout the 20th century (1994, Tables 9 and 10, pp. 14-15). This point is easily integrated with other works, as Narin et all (1997) that show the increasing role of science and technology as sources of economic development.[3]

This introduction explains why an investigation on the relationship between science, technology and development may use NSI as a guiding concept. As a synthesis of national technological capabilities, innovation systems may be a useful source for modeling economic growth fuelled by science and technology.

This paper's model is a result of previous work: Bernardes et all (2003) present a discussion concerning science and technology and less-developed countries, Ruiz et all (2005) initiates our modeling elaboration, Ribeiro et all (2006a) concludes this elaboration and suggests a first model and Ribeiro et all (2006b) cluster countries in three different "regimes", representing different stages of NSI formation.

2. THE CORRELATIONS BETWEEN SCIENCE, TECHNOLOGY AND THE WEALTH OF NATIONS

Statistics of patents (a proxy of technological capabilities) and papers (a proxy of scientific capabilities) summarize the main features of national systems of innovation. Of course, papers are not a perfect measure of scientific production, and patents are not a perfect measure of technological innovation. The literature has both used these data and warned about their problems, limitations and shortcomings (see Möed et all, 2004). Scientific papers, the data collected by the ISI, have various shortcomings, from language bias to the quality of research performed: there could be important research for local needs that does not translate in international papers, but only in national publications not captured by the ISI database.

There is a large literature on the problems of this indicator. Patents, the USPTO data, also have important shortcomings, from commercial linkages with the US to the quality of the patent: again, local innovation necessarily is limited to imitation in the initial phases of development, and imitation or minor adaptations do not qualify for a patent in the USPTO). Therefore, this paper

[3] See references on this subject in Bernardes et all (2003).

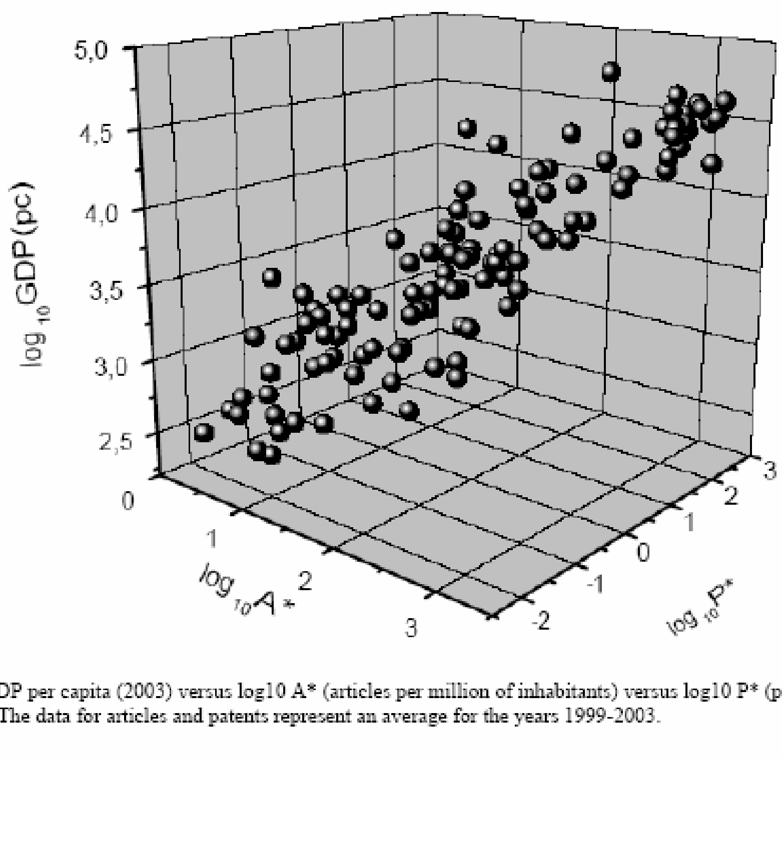
acknowledges these important limitations, and this literature must be kept in mind to qualify the results discussed in the next sub-sections. Despite these problems, these two datasets appear to provide useful information for research.

This paper gathers data of papers and patents for 183 countries between 1999 and 2003. The option for collecting a broader sample of countries includes countries from different stages of development and allows a comparison between developed and less-developed countries, including the transitional position of catching up countries. This data set uses the average for the period 1999-2003, in order to include more countries, mainly those less developed, with very low scientific and/or technological production.

Fig. 1 shows a three-dimensional plot, where the log10 of the GDP per capita (US$, PPP, according to the World Bank, for 2003) is plotted against the log10 of the number of articles per million of inhabitants (A*) and the log10 of the number of patents per million of inhabitants (P*). The data are an average for the years 1999-2003. Only countries with data available and scores different from zero are represented.

Figure 1 shows a strong correlation between science, technology and wealth of nations. Table 1 shows a Correlation Matrix between GNP, patents, articles, and population. There are strong relationships among these variables, which means that there is some system that connects them. Figure 2 shows the projection of these data on the articles-patents plane. Ribeiro et all (2006b) apply a super-paramagnetic clustering technique and find three groups of countries. Hence, they suggest there are three "regimes" that summarizes different levels of development and different types of NSI.

FIGURE 1
GDP per capita vs. Articles vs. Patents (1999-2003)



Plot of log10 GDP per capita (2003) versus log10 A* (articles per million of inhabitants) versus log10 P* (patents per million of inhabitants). The data for articles and patents represent an average for the years 1999-2003.

TABLE 1

Correlation Matrix

	GNP	GNPpc	POP	PATpc	ARTpc	PAT	ART
GNP	1.0000						
GNPpc	0.3606	1.0000					
POP	0.2689	-0.0786	1.0000				
PATpc	0.6578	**0.6752**	0.0385	1.0000			
ARTpc	0.2631	**0.8053**	-0.0726	**0.7084**	1.0000		
PAT	**0.9691**	0.3015	0.1550	0.6577	0.2037	1.0000	
ART	**0.9869**	0.3950	0.2804	0.6743	0.3335	**0.9380**	1.0000

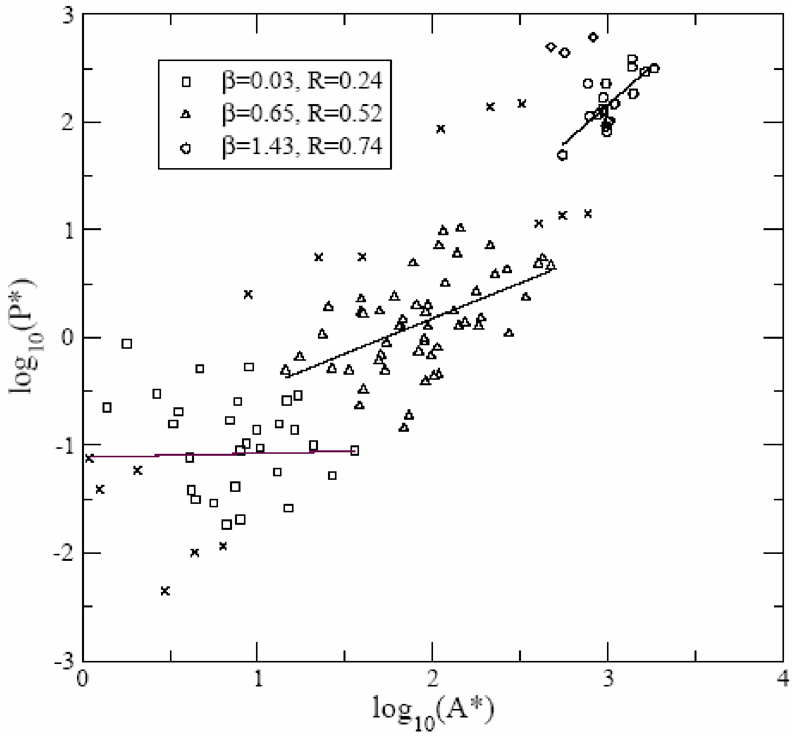
Data Source: ISI, USPTO and World Bank.

These "regimes" say that there are different mechanisms inside NSI. The interactions between science and technology seem to be operating more fully in the countries of the most developed regime (regime 3, represented by squares in Figure 2). Conversely, countries in clusters represented by circles (regime 2) and by triangles (regime 1) lack critical mass in the scientific infrastructure that weakens (or even blocks) the feedbacks between science and technology that pushes economic growth.

Ribeiro et all (200b) suggest that as the "regimes" changes, the number and the channels of interactions between scientific infrastructure, technological production and economic growth also change. As the country evolves, more connections are turned on and more interactions operate. The highest regime is the case where all connections and interactions are working. As long as the development takes place, the role of other aspects, e.g. natural resources, in the causation of economic growth decreases. As a country upgrades its economic position, its economic growth is increasingly caused by its scientific and technological resources. The feedbacks between them contribute to explain why the modern economic growth is fuelled by strong scientific and technological capabilities.

FIGURE 2

Three Regimes (1999-2003)



Note: Clusters obtained in applying the super-paramagnetic clustering technique. Three main groups are clearly distinguished in this figure. The triangles represent countries in regime I, circles stand for those in regime II, and squares represent countries in regime III. Note that a small group of three countries split at the top of the figure. They are Taiwan, Japan, and the United States. For details, see Ribeiro et all (2006b).

3. SIMULATION MODELS OF ECONOMIC GROWTH

Section 1 explains why NSI summarizes technological capabilities of countries. Section 2 presents data that are reliable proxies of the main features of NSIs and of their general relationship with economic development. This leads us to the next step of our inquiry: the investigation of the causal links between science, technology and the wealth of nations. The evolutionary economists, in a tradition pioneered by Nelson & Winter (1982), have used simulation techniques to investigate economic change.

Nelson and Winter explain why the use of simulation techniques is adequate for evolutionary theorists. The main reasons to opt by simulation techniques are: theoretical concerns ("some strong qualitative beliefs about a number of components of the model" without being "rigid about the precise form they should take", p. 207), tractability, possibility of manipulation of certain variables of the model, and the possibility of "generating macro aggregates … through the route of building them up from microeconomic data" (pp. 207-209). They warn against "the most serious problem with many simulation models": lack of transparency (p. 208). But, it is possible to "aim for and achieve a considerable amount of transparency in a simulation model by keeping it relatively simple and clean" (p. 208).

Simulation models have been used widely as tools for investigation of firm competition, path-dependence, market structure, technological change at firm and industry levels etc. These are lines of inquiry introduced by Nelson & Winter (1982, specially Part III: Schumpeterian competition). Nelson (1995) and Dosi (2000) are good surveys of this literature. Silverberg & Verspagen (2005) present an updated version of this line of inquiry.

Our line of investigation goes in another direction: models of multi-country growth. Nelson and Winter also pioneered this line, with their "evolutionary model of economic growth" (1982, chapter 9). To simulate the United States economy between 1909 and 1949, Nelson & Winter's model involves: (a) 35 firms, producing the same homogeneous product (GNP), using labor and capital; (b) firms with a certain productive technique and a stock of capital; (c) a simple decision rule; (d) a wage rate; (e) gross returns to capital and (f) transition rules (resulting from search procedures and investment rules (pp. 209-217). The model generates "aggregate time series with characteristics corresponding to those of economic growth in the United States" (p. 226).

Since 1982 there is a stead growth of the literature using evolutionary models and simulation techniques. However, models concerning growth of nations are relatively scarce; an important exception is the work of Aversi et all (2000). Built upon stylized facts summarized by Dosi et all (1994), they present a multi-country model that "tries to move some steps in this direction by microfounding country dynamics on some stylized company specific processes of innovation and imitation" (p. 535). This model simulates one world economy with L countries, each country with M sectors and n firms. The model is very detailed in its specifications, defining the procedures for search and imitation, the behavior rules ("totally routinized": R&D investments, prices, firms competitiveness and firms growth), market dynamics, aggregate dynamics and national accounts and the general properties of the model (endogenous technological shocks, shocks propagation, sources of persistence and non-linear processes of interactions among firms and characteristics of new firms). Their model has 23 equations.

Our model differs from the Aversi et all model in a very simple way: while they try to add microfoundations to the model, our model is built upon the synthesis of technological capabilities represented by the NSI. Our line of inquiry (hints of causal links running from science and technology to GDP) led us to search for parsimonious models, which mean few equations, variables synthetic enough to describe key features of modern economic development, therefore the use of NSI and their two dimensions (science and technology) to summarize these relationships.[4]

4. INNOVATION AND IMITATION IN A MULTI-COUNTRY MODEL

This section presents a new model, based on our previous work. Ruiz et all (2005) is the first draft and Ribeiro et all (2006a) present our first developed model. The insights and discussions provided by these previous papers contributed for an improvement: the main difference of our new model is the way T changes, a key variable representing each country's NSI. In the former model, a

[4] In a presentation of one preliminary version of this model in a Conference of Physics (Ruiz et all, 2005), some participants presented tough criticisms against the model because it had too many variables - just three…

country only would try to improve its technological position if its income were reduced. This reasoning is in line with Nelson & Winter 1982 model, where "only those firms that make a gross return on their capital less than the target level of 16 percent engage in search" (p. 211). This seems not to be the case, as theory and evidence show that leading countries innovate in a very systematic way. Thus, in this version of the model, a country may improve its technology without suffering from income reductions.

In our model, the world economy is modeled as a network of agents (countries), and the interactions among these countries are represented by functions that connect their prices, demands, technologies, and incomes. Starting from random values for the country technology, the artificial world economy self-organizes itself and creates hierarchies of countries that are closer to the real world (as identified by our empirical findings). In the beginning of the simulation, there is an unbalanced network, each point (a country) in the configuration space with its own set of features. However, interactions are necessary (within countries and between them) to produce a specific hierarchy. This hierarchy may correspond (or not) to the world captured by data (GDP per capita).

The basic variables for each country are (a) Li, its population or labor force; (b) its income or gross domestic product Yi (the wage or per capita income being Wi = Yi/Li); (c) patents and (d) scientific papers. The country economic structure is given by four equations:

4.1. Country Economic Structure

4.1.1. Price and Production

The equations that define the level of production and price are:

$$Q_i = (T_i \,.\, L_i) + V_i \qquad (1)$$
$$P_i = (Y_i \,/\, Q_i) \qquad (2)$$
$$P_i = Yi \,/\, [(T_i \,.\, L_i) + V_i]$$

Where, Q_i is the amount of goods produced by country i, T_i represents country technology, L_i stands for population or labor force, and V_i is the unsold good of previous period. The country income (US$ GDP) is Y_i and P_i is the price of one unit of good Q_i. Population (or labor force) is constant, thus Q_i depends mostly on T_i, which is an output of the NSI. The price level is set by an adaptive rule: everything else constant, unsold stocks and decreasing national income reduce prices and increase competitiveness, and falling inventory and raising income do the opposite.

4.1.2. Competitiveness

The country competitiveness Ci has an inverse relation with its price:

$$Ci = (1 \,/\, Pi) \qquad (3)$$

The global competitiveness Cg is the country competitiveness C_i weighted its market share M_i (the participation of the country in the world economy measured by its income):

$$M_i = Y_i / \sum Y_i$$
$$Cg = \sum(M_i \, . \, C_i) \quad (4)$$

4.1.3. Technological Change

Countries change their technology in order to increases its competitiveness and wealth. To do so, it must change its technology, which depends on the previous level of its own knowledge (T_i) and on the technological information grabbed from international sources (Tg). Country capabilities to create new technologies are represented by patents and articles per capita (PAT_i and ART_i), which are proxies for scientific capabilities and firms capabilities:

$$Ti_2 = Ti_1 + Ni \quad (5)$$
$$N_i = (Tg \, . \, PT_i \, . \, AT_i)^{1/3}, \text{ where } 0 < N_i \quad (6)$$
$$Tg = \sum(M_i \, . \, T_i) \quad (7)$$

The coefficient N_i is a proxy to the NSI, which corresponds to the countries' innovation capabilities (ATi and PTi) plus the spillovers of technologies of the global economy (Tg). Therefore, the national system of innovation Ni summarizes the country capabilities to imitate and innovate.

4.1.4. Income

The country income is Yi plus the income not spent in the previous period Si (savings). The wage (or per capita income) is the country income distributed among its labors (population).

$$Yi = Ki + Si \quad (8)$$
$$Wi = Yi / Li \quad (9)$$

The global income is the sum of all country incomes:

$$Yg = \sum Yi \quad (10)$$

4.2. Country Demand, Capital and Savings

4.2.1. Market Share and Demand

A replicator dynamics equation models the changes of country market share (equation 11). The replicator dynamics is routinely used in evolutionary game theory, versions of cobweb models and other dynamic sets. It is used to represent sluggish changes in behaviors; in this case the σ is the speed of the market share changes to asymmetries in the country and the global competitiveness.

$$M_{i2} = M_{i1} \, . \, [1 + \sigma \, . \, \{(C_i / C_g) - 1\}], \text{ where } 0 < \sigma < 1, \text{ and } \sum Mi = 1 \quad (11)$$

Thus, the country demand Di (unit of goods) is given by:

$$Di = Dyi / Pi$$
$$Di = (Mi \, . \, Yg) / Pi \quad (12)$$

4.2.2. Capital, Inventory and Savings

There are recurrent disequilibria on the amount of goods demanded and supplied. Thus, three simple rules were created:

When $Di = Qi$, then: $Ki = Pi \, . \, Qi = Pi. \, Di$, $Vi = 0$ (13)

When $Di > Qi$, then: $Ki = Pi \, . \, Qi$, $Vi = 0$ (14)

When $Di < Qi$, then: $Ki = Pi \, . \, Di$, $Vi = (Qi - Di)$ (15)

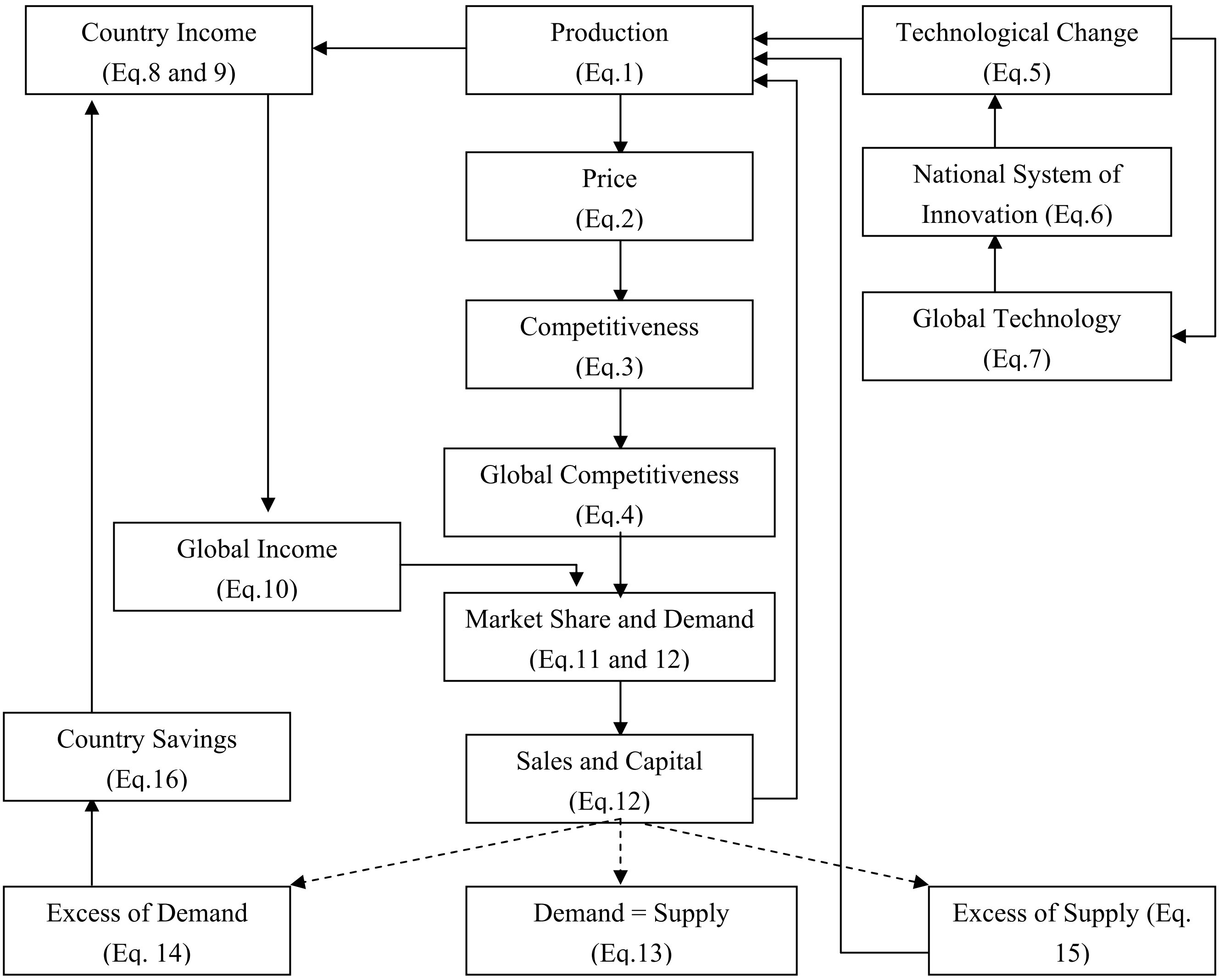
$$Vg = \Sigma \, Vi = \Sigma \, (Qi - Di) \quad (16)$$
$$Sg = \Sigma \, Si = \Sigma \, [Pi \, . \, (Di - Qi)] \quad (17)$$

Where Ki is the capital or sales, Si and Sg are the country and global savings (income not spent), and Vi and Vg are the country and global stock of unsold goods. The country savings is proportional to its market share Mi:

$$Si = Sg \, . \, Mi \quad (18)$$

In the first case above (equations 13), all goods are sold ($Vi = 0$) and there is no savings ($Si = 0$), which means the system is in equilibrium; thus $Sg = 0$ and $Vg = 0$. In the second case (equations 14), there is an excess of demand ($Sg > 0$), there is no inventory ($Vi = 0$) and consumers do not spend all their incomes, which means savings Si return to countries (equation 18). In the third case (equation 15) there is an excess of supply ($Vi > 0$) and all income is spent ($Sg = 0$). At the equilibrium there would be no inventory ($Vg = 0$) and no savings ($Sg = 0$). However, as one can check, the equations 5 to 7 keep the system out of the equilibrium.

Draw 1: Model Structure



5. SIMULATIONS AND RESULTS

We choose the initial values of our simulations (initial countries' incomes, $Y_t^{\,0}$). The system evolves accordingly the algorithm described in Section 4 and we monitor the evolution of income (Y) and savings (S), until the system reaches a stationary state. Typically (as in Ribeiro et all, 2006a), we use three alternative initial conditions for the wealth of nations:

a) all countries start with their real GDPs;

b) all countries have the same GDP – each country receives $\sum_{i=1}^{N_c} Y_i / N_c$, where N_c is the number of countries (183); and

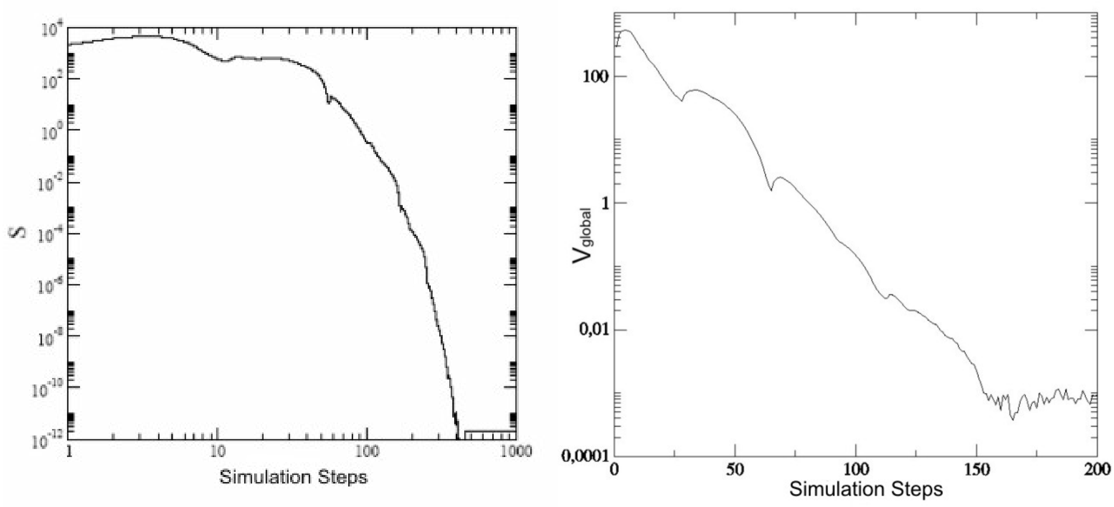
c) we give random values to Y_0.

In all simulations the initial level of technological development (T_0) is randomly selected between (0,1].

5.1. First Simulation: Initial Random GDPs

In a first simulation exercise, we present the case of initial random values of Y_0 (option number 3, above). Figure 3a shows the evolution (1,000 simulation steps) of global savings Sg for this case. In the beginning (the first 70 simulation steps) there are huge differences between supply and demand. This mismatching between supply and demand is represented by the high values of global savings (Sg). As the simulation goes on, the global savings decrease significantly and the system evolves to a stationary state (near 400 simulation steps). Figure 3b shows a similar pattern for unsold goods.

FIGURE 3
Savings (3a) and Unsold goods (3b)
(1,000 simulation steps, logaritmic scale)

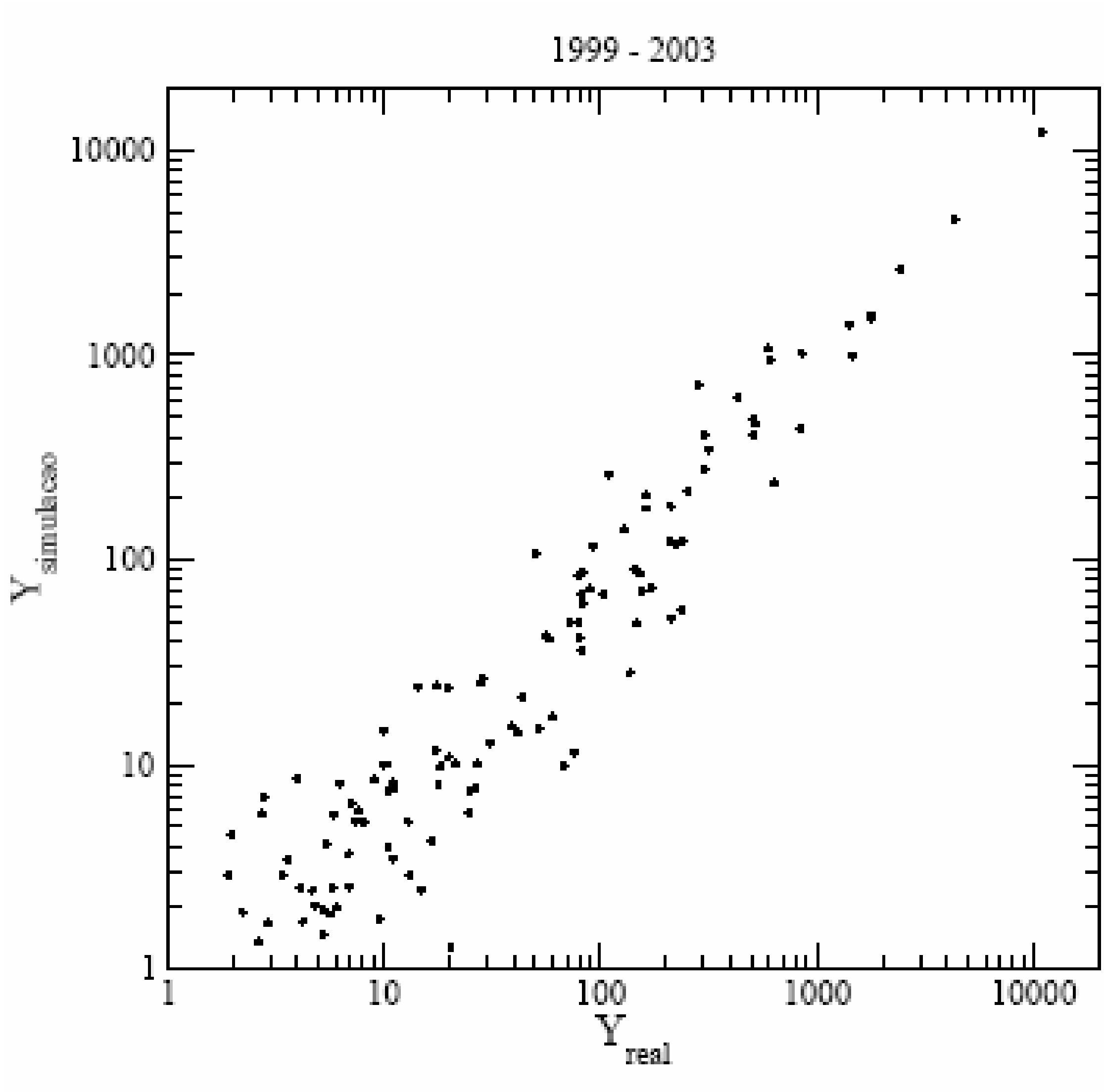


As the system reaches a stationary state (according to Figures 3a and 3b), we compare the real and the simulated values. Figure 4 presents this comparison (Y_{real} versus $Y_{simulated}$), after 1,000 simulation steps. There is a strong correlation between the real and simulated values (β = 1.10 and R=0.99). This strong correlation suggests that the assumptions regarding the guiding force of technological capability (T) to organize the simulated world replicating the real world.

Regarding the correlation between simulated and real values, Figure 4 shows that for higher Y, there is a smaller dispersion of points (countries) vis-à-vis the linear regression. This suggests that for richer countries the role of science and technology as source of their wealth is stronger than poorer countries. Inversely, for lower Y there is a greater dispersion of points (countries) vis-à-vis the regression line. This greater dispersion may indicate that for these poorer countries "other" factors beyond science and technology (natural resources endowments, geopolitical conditions, etc) have stronger role as source of their wealth. These findings seem to be in line with a simple model presented in a previous paper (see Bernardes & Albuquerque, 2003).

Regarding the inclination of the regression line (β = 1.10), Figure 4 shows both overestimation and underestimation of wealth. The wealth of richer nations is overestimated in 10%, while the wealth of the poorer countries is underestimated in 10%. This divergence may be explained also by the exclusion of “other” factors from our model. As in our model only technological capabilities (T) determine the wealth of nations, thus technologically stronger countries tend to be overestimated. On the contrary, countries whose income depends on “other” factors have them not taken into consideration, hence the underestimation. Indeed, our model should produce an inclination greater than 1, given its assumptions (“other factors” play no role).

FIGURE 4
GDP (Y, US$ billion), real and simulated values
(1,000 simulation steps, logaritmic scale)



This first exercise shows us that the system tends to a stationary state (a non-chaotic state), an essential property of a working model.

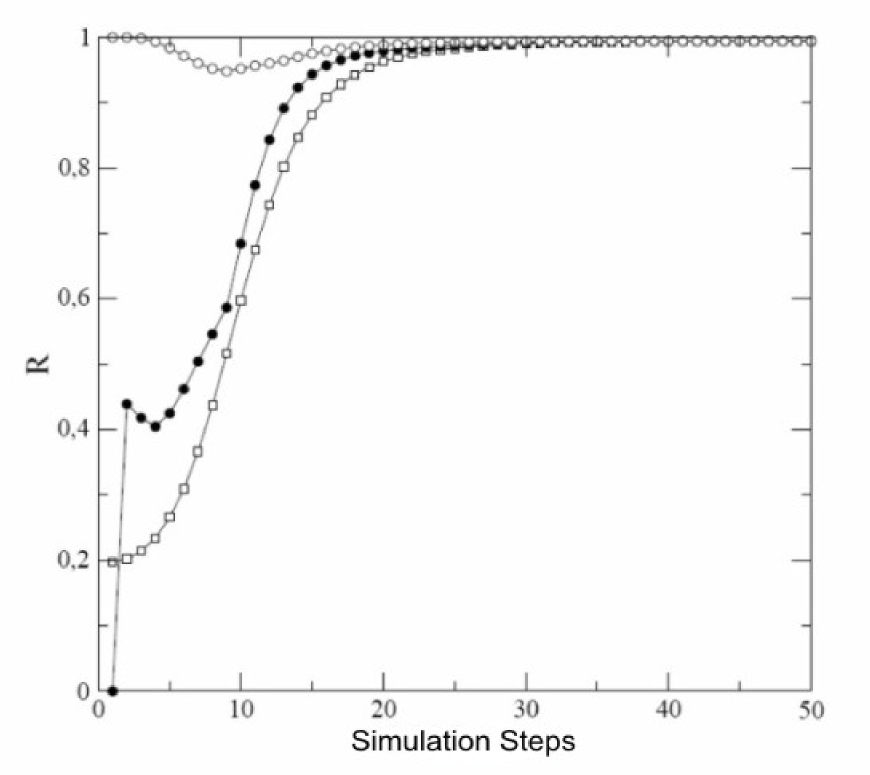
5.2. Second Simulation: Three Different Initial GDPs

In this second simulation exercise, we compare the correlation between the real and the simulated world created from the three initial conditions for $Y_i(t = 0)$. Figure 5 shows the evolution of the correlation coefficient between the real and simulated wealth for these three paths: (a) open circles for initial GDPs equal to real GDPs; (b) closed circles for all countries with the same initial GDP; and (c) open squares for initially randomly selected GDPs.

Predictably, Figure 5 shows that during the first simulation steps the correlation between real and simulated GDPs are very different: high correlation for real GDPs as initial values and low correlation for the other two starting points. Asymmetric initial conditions underlie this initial different correlation. However, as the simulation evolves, the correlation values converge to the same (and high) correlation value. This represents a very important point: our model is robust in relation to initial conditions. When we feed our model with the real data for population, scientific and technological production, it does not matter from where the simulation begins: it will always build a simulated world that replicates the real world. In other words, these three variables are enough to define the world wealth distribution in a stationary state. All curves converge to the correlation in the neighborhood of R=0.99 and to an inclination near 1.10.

FIGURE 5

Correlation between Real and Simulated GDPs per capita



Note: Simulations starting with equal, random and real GDPs per capita values.

This second exercise shows that the system always replicates the real world, independent of the initial conditions. As our model does not control variables like GDP, the system is robust regarding its initial conditions.

5.3. Third Simulation: Real and Random Values for Population, Scientific and Technological Production

In this third simulation exercise, the initial GDPs values are the real ones. In this exercise what we change are the values for population (L) and for scientific and technological production (T). Figure 6 shows the correlation between the real and simulated Y obtained for four different paths. During the first simulation steps the correlation is high in all four cases because the real GDPs are the starting points. Divergence regarding correlation is generated just after 40 simulation steps.

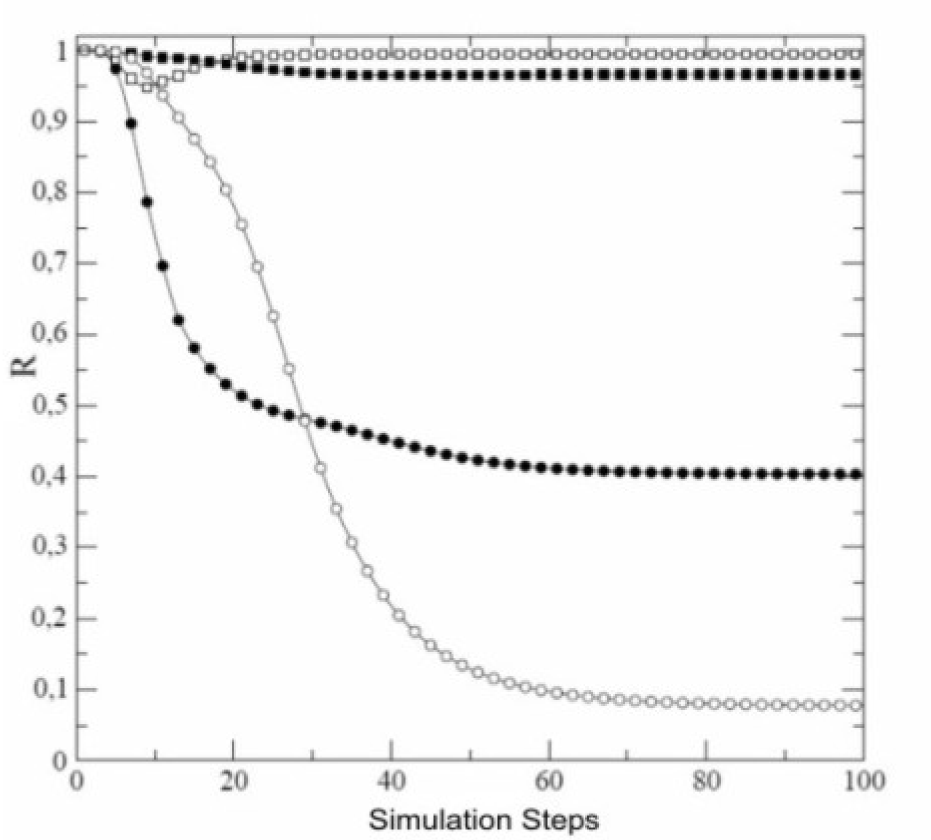
The first path is represented by open circles: the model is fed by random values for population and for scientific and technological production. As the system evolves, the correlation between real and simulated wealth falls, reaching R = 0.1 around the 100^{th} iteration.

The second path is represented by closed circles: random values for scientific and technological production but real values for population. The correlation also falls as the system evolves, but reaches R=0.4 around the 100^{th} iteration.

In the two last paths the models are fed by real values for science and technology. In the third path, represented by full squares, populations are defined randomly. The correlation is high (R = 0.96) around the 100^{th} iteration. Finally, in the fourth path, population and science and technology are real values, and the correlation is R = 0.99 (a correlation similar to the obtained in the two previous exercises, see topics 5.1 and 5.2, above).

FIGURE 6

Correlation between Real and Simulated GDPs per capita



Note: Simulations starting with random and real values for population, technological and scientific production.

The comparison between these four paths suggests the role and the weight of each variable as a determinant of the wealth of nations, stressing the importance of science and technology. This exercise is the most important to test this paper's conjecture.

In sum, this section shows us that: a) the system tends to a stationary state (a non-chaotic state); b) the system always replicates the real world, independent of the initial conditions; and c) the role and weight of science and technology as a determinant of the wealth of nations.

6. CONCLUSIONS AND AGENDA FOR FURTHER RESEARCH

The findings so far: (a) the data and the initial simulation supports an important role for science and technology in the determination of the wealth of nations; (b) the model is able to replicate the real world starting from the variables describing science and technology; (c) this model was tested to investigate whether or not other variables would have similar effects (the hierarchy of countries is always replicated by our model when fed by science and technology and it is not replicated when random variables are used).

Regarding the model suggested in Section 4, the simulation exercises show that it is able to replicate the world income distribution without a priori information about this distribution, the algorithm is consistent as the results are non-trivial (stationary state is independent of initial conditions). The model simulates a world that has high correlation with the real world. And the model is parsimonious, as we obtain the world income distribution (R=0.99) feeding the system only with data for population, patents and scientific papers.

Regarding this paper's conjecture on the role of science and technology as a determinant of the wealth of nations, the exercises show that science and technology are good proxies to guide the system to find its stationary state. Furthermore, as the third exercise shows, science and technology are more important than population to define the world's income distribution.

Finally, this new version improves the model presented in Ribeiro et all (2006a) because T is now defined in a way more in line with the evidences of the literature. While in the previous version a country only would try to improve its technological position if its income were reduced, now a country may improve its technology without suffering from income reductions. Then, our model is more attuned to evidences and theory coming from the literature of economics of innovation.

As our model is able to replicate the real world (a static model), these findings support a move towards a next step of our agenda: how to model a dynamic world. This version of our model, with the new way that the NSI-related variables feed the system, is a step in the direction of a dynamic model. The goal of this dynamic model is to replicate the dynamics pinpointed by the data presented in Ribeiro et all (2006b), for the world in 1974, 1982, 1990, 1998 and 2003. Furthermore, two additional steps may be taken: 1) improvements in the quantitative representation of NSIs (the interactions between science and technology may be taken into account within that indicator); 2) introduction of possibility of individual time-paths that would overcome the thresholds identified by Figure 2.

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