Chapter 15
Educational Systems and the Intergenerational Transmission of Inequality: A Complex Dynamical Systems Perspective

Porfirio Guevara and Emilio Porta

Introduction

It is one of the greatest puzzles of our time. Globalization and technological change has lifted hundreds of millions of people out of poverty and improved the lives of many more that, thanks to the internet and advances in education, have joined the global supply networks everywhere, mainly in developing countries during the last half-century. Paradoxically, this trend has also intensified internal divisions in society, like those based on income distribution. Individuals with better skills have managed to outstrip unskilled workers as the formers' knowledge has facilitated access to well-paid jobs and investment opportunities. Unskilled workers, on the other hand, are more likely to access jobs that compete more directly with automatic processes performing routine-intensive activities that affect their employment and returns opportunities. The numbers are astonishing; worldwide, some 780 million adults and 126 million youngsters still lack the most basic reading and writing skills (UNESCO, 2015). As a result, income or wealth-based inequalities has been reported on the rise everywhere (Piketty, 2014; Ravallion, 2014). This is a reminder that despite the startling technological advance of the modern world in solving many of today's most pressing scientific and engineering challenges, the complexities of the systems in which most human activities are embedded prevent us from taking full control of even our good intentions to provide inclusive social and economic progress for everyone.

Although social and neural scientists are still trying to disentangle the multiple causes of inequality and policy measures are currently subject to an intense debate, the role of educational systems on human capital in an increasingly technologically connected society are at the center of deliberations (Noble et al., 2015; Porta & Laguna, 2007). Educational systems are one of the main sources of skills and

P. Guevara (✉) • E. Porta
INCAE Business School, Alajuela, Costa Rica
e-mail: porfirio.guevara@consultor.incae.edu; eporta@gmail.com

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productivity available to a country. At an individual level, researchers have long established a strong causal link between advances in school attainment and individual earnings via improvements in productivity, and therefore productivity is crucial to explain how much workers earn.[1] But workers' earnings depend not only on specific issues related to their productivity to perform determined tasks, earnings also depend on the pool of additional workers currently available in a country to accomplish such tasks, for which the underlying educational system is crucial. If, on average, only a reduced fraction of individuals finish the school on time—i.e., there is a sizeable fraction of students that repeats or drops out—then one would expect to see a shallow pool of skilled workers in this country and as a consequence high returns to schooling, which would be one of the main sources of inequality. Moreover, if this process is prolonged over time and it systematically targets specific groups, we just need a dominant positive feedback in the system reinforcing small differences to attain the intergenerational transmission of inequality.

Feedbacks are an essential component of any complex dynamical system and positive—or reinforcing—feedbacks have been extensively identified in educational systems (see Koopmans, 2014). Constituent elements in an educational system change and react over time—usually in nonlinear ways—with the collective patterns they create amplifying original differences. One may naturally think, for example, on the influence that the aggregate characteristics of a community has on individual schooling decisions. Students from low-income families are more likely to repeat or dropout the school, starting out at a disadvantage in the labor market and in that way restricting their earnings and likely, those of their offspring. The educational system rewards disproportionally those who complete the process but additionally penalizes extensively who fail to do so as the reverberations of these outcomes are transmitted through generations. Thus the role of educational systems and their efficiencies must be placed at the center of the debate on the transmission of inequalities and social mobility for the purpose of understanding them and designing possible strategies to address them.[2] Consequently, to approach inequality in a relevant dimension our analytical framework must grasp the dynamics of the whole system and not only the behavior of its individual components. Under this perspective two prominent approaches can be applied in the analysis:

(a) Individual-based interventions, which focus on cognitive skills and learning trajectories attained by students during the instruction process

[1] The dominant theory of human capital formation is rooted in economics and owns its relevance to outstanding contributions by Mincer (1958), Becker (1962), and Becker and Chiswick (1964). These celebrated authors established the central role of education to explain earnings' differences and inequalities in society, and their ideas have been subject to mounting empirical scrutiny by authors like Hanushek (2009, 2014), Autor (2014), Ravallion (2014), among others.

[2] By *efficiency* we mean the ability of an educational system to graduate the maximum number of students had children entered school at normal age and advanced one grade each year, without repetition or dropout.

and the influence of school and socioeconomic factors on those trajectories (Noble et al., 2015).[3]

(b) Improving the education production process by enhancing the operational activity of human capital generation at macro level.

The approach we follow in this chapter is of an operational and aggregate nature and thus the second category is the relevant to our analysis. The overall behavior of a complex system cannot be deduced from its constituent elements in isolation—which can be regarded as the emergent property—and therefore the analysis of an educational system can be enriched from a modeling perspective by adopting a macro perspective that accounts for the interactions of its elements. When the relevant unit of study is set to be at aggregate or macro-level, it becomes much simpler to focus on the average performance of the students in a system without losing relevant information for the analysis. Additionally, as the macro-level of any complex system is governed by the laws of physics (Carroll, 2010), once we integrate these laws in our model a certain amount of discipline is imposed in its structure increasing the reliability of simulations over long periods of time since these laws are expected to remain unchanged over time.[4] Thus, complex modeling and simulation grounded on scientific principles offers a sound and reliable methodology to understand the relationship between the structure of an educational system and the behavior driving the intergenerational transmission of inequality, as many of these relationships mainly emerge over long periods of time.

To perform the analysis we present a dynamic, nonlinear system dynamics simulation model for primary education, calibrated for the case of Nicaragua during the period 2000–2010, in a similar fashion to the one described by Guevara, Lopez, Posch, and Zuniga (2014). We also illustrate how the model can be extended to disaggregate population by income/wealth and by their opportunities to finish primary school. We believe this approach will help us understand how educational systems work in reality by making explicit some of the channels and feedbacks that influence the relationship between income/wealth and education across

[3] The individual-based interventions which focus on cognitive skills and learning trajectories attained by students during the instruction process and the influence of school factors on those trajectories have also a great deal of interest in this book. See for instance the analysis of learning trajectories over time and the influence of the classroom interactional context by Steenbeek and van Geert (University of Groningen, Netherlands); or the use of orbital decomposition to study the predictability of learning behaviors and patterns of social interaction in educational settings by Stamovlasis (Aristotle University of Thessaloniki, Greece).

[4] The model complies with the first two laws of physics. The First Law (conservation of the matter) states that the amount of people entering the system must not be different from that that ever goes out, ruling out the possibility that the simulation model creates people artificially due to a human error in the computer code. The Second Law proposes that the entropy of a closed system cannot decrease and time has only one direction (see Guevara, 2014).

generations. Under this perspective, we find insightful to portray (the lack of) equality as a *critical factor* of the human capital process—following Guevara and Posch (2015)—and show how income inequality might impact the overall operational efficiency of the system. Our intention is to draw a methodological line related to the transmission of inequalities from a complex system perspective that can be extended and refined in future studies for the purpose of designing and evaluating policies to tackle income distribution in a country via the efficiency of its educational system. This CDS simulation model thus will allow us to draw alternative causal inferences to those documented in studies using simple correlations as in Hanushek (2009) or Hanushek and Woessmann (2014).

Assessing a complex system's topology using correlational methods is helpful albeit insufficient due to the nature of this study. The interactions we aim to capture in our model are embedded in a complex web of multiple subsystems and variables producing outcomes that feedback to these subsystems and their components. Thus we require information about the multiple components' roles in a system and their mutual and simultaneous interplay which likely go beyond correlational procedures (see Guevara et al., 2014). Another fundamental omission in traditional statistical analysis arises from its static nature. It normally takes a snapshot of the complexities of the human capital process over time and its impact on the transmission of inequalities through generations. In a dynamic context, when skills and opportunities for social mobility are to a great extent determined by the economic or social family background, their effects go beyond the direct impact on the actual individuals perceiving such benefits, as it takes the form of an intergenerational wealth transfer. Therefore we need approaches that explicitly deal with these issues and help us to answer critical questions like:

- How can we model the simultaneous and dynamic interrelationship between the efficiency of educational systems and income distribution?
- What are the consequences of income-based unequal opportunities in education systems dominated by self-reinforcing causal relationships?
- What will happen to the school attainment of current and future generations if such causal relationships are held over the long term?

The current empirical literature does not provide answers to these questions and this study aims to start the debate. The intergenerational transmission of inequality is not less controversial from an academic perspective given its complex nature and multidimensionality. Multiple channels of influence interact via feedback mechanisms making clear-cut conclusions difficult to wage. We argue that inequality and low social mobility are not only bad for those individuals born in disadvantaged households; it is also detrimental for the efficiency of the whole educational system which in turn may have implications for the long-term productivity and social and economic progress of countries. As we show next, Nicaragua presents several characteristics that make the country suitable for the analysis from a complex dynamical systems perspective.

The Case of Nicaragua

It is very much the case in Latin America and other regions in the world that more income inequality is associated with less opportunities for the new generations to advance due to low educational mobility (see Fig. 15.2). Low educational mobility in this context means the family background is determinant and a large fraction of socioeconomic advantages and disadvantages are passed on from parents to children, generating a self-perpetuating behavior in the system. In short, more inequality at any point in time is associated with a greater transfer of educational (and consequently economic) status across generations.

The Nicaraguan educational system is a conspicuous case in this regard as it shows certain regularities in its behavior suggesting that an underlying structure is driving the observed outcomes. For example, (1) income and wealth are unequally distributed among the Nicaraguan population and this condition is fairly stable across time and directly projected in the school population (Table 15.1) that reinforces these results. While some improvement in equality is observed over the past three decades, income inequality still remains large as shown by the Lorenz curves in Fig. 15.1.[5] The closer the Lorenz curve is to the equal-distribution line the better the income distribution in the country. So for the last two years that information is available, 2005 and 2009, the country improved its income distribution (2) Most individuals in the upper quintiles of income start and complete primary education without delay, as represented by high promotion and low dropout and repetition rates, while those in the lower quintiles of income are predominantly underperforming in the same terms. In Table 15.2 children in the first quintile (the poorest) have completion rates below 75 % while the richest show promotion rates of 95 %. Similarly repetition and dropout rates are 3 to 7 times higher in the lower quintiles than in the highest quintiles, respectively. These differences tend to remain stable over time. Likewise, Nicaraguan families with high educational attainment tend to have fewer and better educated children

Table 15.1 Nicaragua 2001: Primary-school enrollment by household wealth

Quintile	Students	Percentage (%)
I (poorest)	231,672	26.13
II	225,540	25.44
III	198,213	22.35
IV	161,575	18.22
V (richest)	69,683	7.86
Total	886,683	100.00

Source: LSMS 2001

[5] The Lorenz curve is often used to represent income distribution and shows the proportion of income or wealth (y %) accrued by the bottom x % of the population. A perfectly equal income distribution would be one in which the bottom x % of society would always have x % of the income and can be depicted by the straight line $y = x$ which is called the ”line of *equidistribution*”.

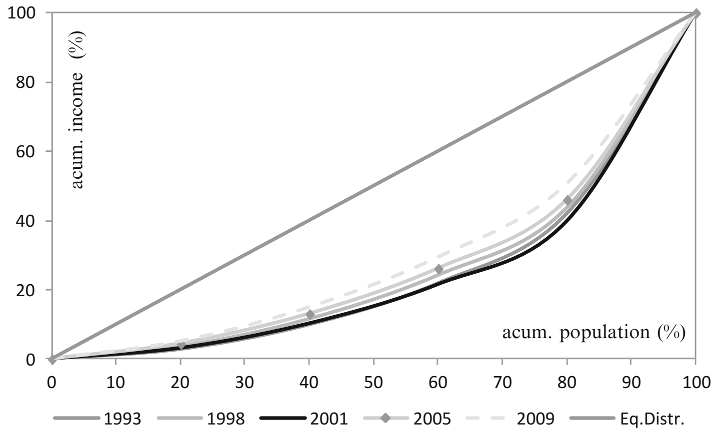

Fig. 15.1 Nicaragua 1993–2009: Lorenz curves. Source: constructed with data from SEDLAC (2015)

Table 15.2 Nicaragua 2001: promotion, repetition, and dropout in primary by household wealth

Quintile	Promotion	Repetition	Dropout
I (poorest)	74.5	9.7	14.9
II	83.7	6.3	9.5
III	87.0	4.2	8.5
IV	92.1	3.2	4.5
V (richest)	94.9	2.8	2.2

Source: Living Standards Measurement Survey (LSMS), 2001 (Porta, Arcia, Macdonald, Radyakin, & Lokshin, 2011)

and these children tend to repeat and dropout less than those in less educated families (World Bank, 2001). Consequently, educational and social mobility is very low in the country, Nicaragua scores very low in mobility (very high position in Fig. 15.2) even respect to other Latin American countries to which it is often compared (Andersen, 2001; SEDLAC, 2015). So Fig. 15.2 shows countries ranked from low to high inequality (left to right): Argentine, Peru, Nicaragua, and Bolivia being the most equal countries, and Brazil, Paraguay, and Honduras being the least. On the other hand, moving along the vertical axis from bottom to top represents a movement from more mobility in educational status across generations to less educational mobility. In countries such as Argentine, Bolivia, and Ecuador, the correlation between parental economic status and the adult outcomes of children is the weakest: Less than 10 % of any educational advantage or disadvantage that a father had had is passed on to a son in adulthood. In contrast, in Honduras, Panama, and Nicaragua, more than 15 % of any advantage or disadvantage is inherited by the next generation. If a father had twice the average of years of education in Bolivia, for example, he would expect his son to end up having only about 8 % above average; in Nicaragua, this would be more than 20 %. In such settings the Nicaraguan poor are

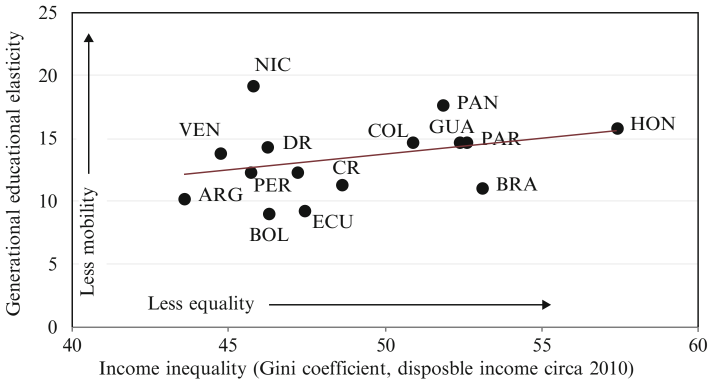

Fig. 15.2 More inequality is associated to less mobility in Latin America. Source: constructed with data from SEDLAC (2015) and World Bank (2015)

more likely to see their children growing up to be the next generation of poorly educated people, and the rich are more likely to see their children at the top rungs of the social ladder. Therefore, the large disparities that exist in the education system of Nicaragua just replicate the inner pattern of income inequality. This result also holds on a global scale and among regions as confirmed by Porta (2011) in more than 80 countries and it is what we would like to capture in our model.

The Model

When attempting to understand the complex dynamic behavior of an educational system we first need a fair understanding of the underlying structure—in term of its stocks, flows and feedbacks—that may influence the system's observed behavior. A *stock* variable is something that can be accumulated, i.e., water in a reservoir or population in a country. It is measured at one specific time and that measurement represents a quantity existing at that point in time (say, persons). A *flow* variable is analogous to the mathematical concept of *rate*, which measures a variable over a period of time and when coupled to a stock, the flow variable is measured in the same units of the stock *per time unit* (say, persons per year). Finally, feedbacks are closed chain of interactions between the elements of a system forming a loop that can be of two classes: positive and negative. Positive feedback loops are self-reinforcing (more population—more births—more population). Negative feedback loops are self-correcting as they counteract change (larger population—more deaths—smaller population).

Stock and flow variables are natural candidates to be included in any educational system structure because *time* is intrinsically embedded in these variables and it is possible to identify and capture the components' mutual influences as well as their direction of influence.

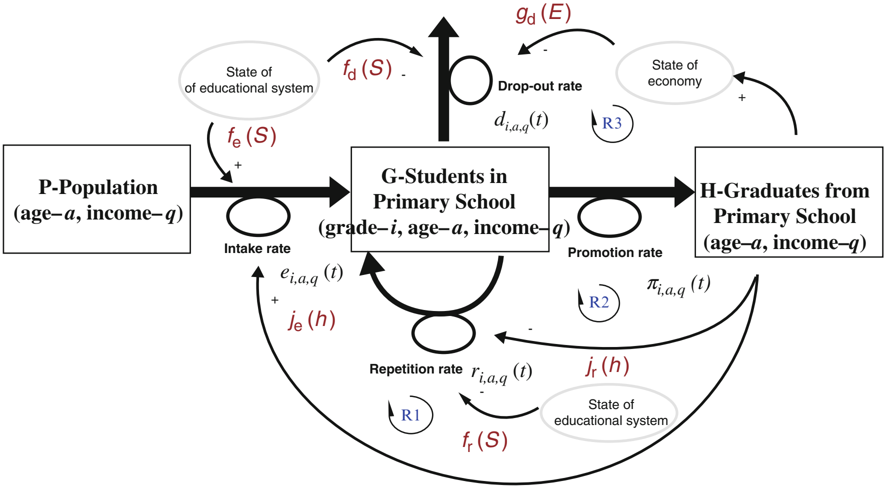

Fig. 15.3 State variables (stocks) are represented by *rectangles* and are disaggregated by age-*a*, income-*q*, and grades-*i*. Flows change the values of these stocks and are represented by *arrows*. The other variables such as the *state of the education system*, *state of the economy*, and *graduates from primary school* (human capital, *h*) are the critical factors that modify these flows (nonlinearly) and generate positive feedbacks such as R1, R2, and R3 (reprinted with permission, see Guevara et al., 2014)

A well-documented feedback in demographic educational modeling and simulation is the *assortative mating* characteristic that suggests that educated families are more likely to send their offspring to school where they can meet peer students, or in its dynamic version—the *role model effect*—as more educated households place education a top priority for the next generations (Behrman & Rosenzweig, 2005; Durlauf, 1998, Morrison, 2008). In the context of a causal loop diagram, we can capture this effect using the population of literates whose effects influence directly the system's transition rates (see reinforcing feedbacks R1 and R2 in Fig. 15.3). High literacy in a country reduces repetition rates because more literate parents persuade and are persuaded by their peers to support children's academic activities and their collective efforts are more effective (Durlauf, 1998; Oreopoulos, Page, & Stevens, 2006). This leads to an improvement in promotion rates leveraging primary graduates which also increases the amount of literates in the population. A second causal loop effect captures the influence of educated population on aggregate economic growth (Dowrick, 2004). A country with a sustained economic growth is more likely to improve households' budgets and support youngsters' education because there will be more enrollment and less dropout. In such setting more students finish primary school *ceteris paribus* (R3 in Fig. 15.3), and the share of persons with complete primary education increases improving human capital in the country. More human capital in turn improves economic growth in the long run when a more educated labor force exploits better economic opportunities in the market and more efficiently, boosting up the country's productivity. Notice that extending the previous feedbacks loops to include income-based differences in a population is straightforward as we only have to disaggregate the same variables included in these loops by wealth or income percentiles. These positive feedbacks spawn the conditions for income-based feedbacks that would induce an intergenerational transmission of inequalities in society.

To grasp how the whole structure works in an educational context one may begin dividing up the entire course of school levels into grades, represented by stock variables through which a population flows via transition rates: intake, repetition, dropout, and promotion. Clearly, these transitions occur from the first to the last grade in school; flow-variables capture these processes via differential equations for intake (e), repetition (r), dropout (d), and promotion (p)—as shown in Fig. 15.3—while feedbacks are the mechanisms driving these dynamical processes. This chapter uses the primary school completion rate (PCR)—which measures the number of graduates from primary school in a given year as a proportion of the total number of children in the population reaching the appropriate age for graduation—as an output indicator to track progress, efficiency, and the dynamics of education systems. The system dynamics model presented here builds upon Guevara et al. (2014) who presented a model of the Nicaraguan educational system originally disaggregated by age and grade only, which we extend by disaggregating all population stocks and their respective inflows and outflows by quintiles of income.[6] An income-disaggregated population thus is more relevant for our purpose because beyond the simple age-grade disaggregation, a richer picture emerges due to the indisputable relationship between each income-group and the educational transition rates: intake, repetition, dropout, and promotion. As we climb up the ladder of income quintiles in the system, from the lowest to the highest, intake rates increase unambiguously while repetition and dropout decrease monotonically.

Three *critical factors* are included in the model: the *state of the education system (S),* the *index of human capital (or the state of adult literacy)* in the country (h), *and* the *state of the economy (E).*[7] To explicitly capture feedbacks and nonlinear relationships in the model, all parameters governing transition rates in the model are specified through the multiplicative interaction of their respective initial values (at time $t = 2{,}000$) and the nonlinear effects that the critical factors exert on each parameter through a number of functions $f, g, j,$ that make explicit the nonlinear impact of variables S, E, and h on enrollment (e), repetition (r), and dropout (d).

[6] We calibrated the model using a complete set of quantitative information circa 2000 (most of data used in the model comes from the 2001 LSMS). Before 2001, primary-school data available were not disaggregated by income.

[7] A particularity of these factors is that they cannot be developed or purchased instantaneously; they resemble stocks, which thus must be accumulated over time to reach a particular level. For instance, the *state of adult literacy* in a population cannot be raised immediately; it has to be developed through the transmission of basic learning capabilities on to children, which takes several years. So to explicitly use adult literacy as a critical factor in this model, the flow of primary school graduates is accumulated in a stock.

These critical factors interact nonlinearly with the model components in a closed chain of causal relationships. This is explained in some detail next (Fig. 15.3).

The state of the education system (S) indicates the presence of adequate physical space, supporting personnel, and all related amenities (power, water and toilets, chalkboards, chairs, etc.) that make school activities suitable for students. School infrastructure in this model comprises a stock that increases with newly built classrooms and decreases with those that wear out after a period of 20 years of activity. Classroom requirements are measured considering the actual amount of students in the system and an observed good practice of maintaining an average of 30 students per classroom. "Saturated" classrooms reduce enrolment and increase repetition and dropout.

The *index of human capital* (h) measures the share of graduates from primary school as a proportion of the relevant population. This share has a direct influence on enrollment and repetition. This index also affects dropout indirectly via the state of the economy (R3 in Fig. 15.3). Currently enrolled students in primary education have only three possible directions r, d, or p. While d and p are both exit strategies in this system, the latter is clearly preferred to the former as school graduates are expected to have the skills and experience intended for them. So at the end of the school course, graduate students can be accumulated in a stock we label *human capital*.

The *state of the economy* (E) is used to quantify economic progress through a measure of relative per capita Gross Domestic Product (GDP) in the country. The relative income measure is the per capita GDP at any point in time compared to that recorded in the country in year 2000.[8] GDP grows at 5 % per year on average and this growth rate increases with the education level of the country (Calvacanti, De Abreu, & Veloso, 2013). The intuition behind this formulation is that per capita income and the level of education move in the same direction and this reduces dropout rates as more people can afford education costs (Porta & Laguna, 2007). An increase in primary completion rates raises human capital (h) and more human capital reinforces economic progress at aggregate and individual level (Hanushek, 2009). So when the relative income in the country is low, children are more likely to abandon school as their parents cannot afford the cost of education (Arcia, 2003; Oreopoulos et al., 2006). Countries exhibiting such characteristics would typically exhibit low per capita income and low economic growth.

In this study we aim to understand how coordinated interactions of these critical factors work in a complex dynamic environment like the educational one. Coordination in this setting describes a situation where multiple, interdependent elements interact simultaneously, following their own dynamical processes with limited control by a central authority and with a clear impact on school outcomes. In practical terms, Guevara and Posch (2015) show that coordinated actions that improve infrastructure (state of the educational system, S), economy (state of the economy, E) and literacy (human capital, h) simultaneously are more effective to reach full completion in education.

[8] Real GDP per capita in 2000 was US$1,035 (World Bank, 2015).

However, given that these critical factors follow different accumulation paths (different timing), as we add more critical factors to the system it would take longer for them to line up in the right way to reach a particular configuration, making coordination more difficult. We assess their coordinated impact on the system using the PCR indicator aforementioned over a long period of time (i.e., 2010–2050). When all these properties are merged in a simulation model, the underlying system is expected to bring about features commonly observed in complex systems like tipping points, phase transitions, etc.

Simulations

Baseline Scenario

Under the baseline scenario, the model exploits all assumptions and parameter values used for calibration along with an average economic growth rate of 5 % (see Appendix, Tables 15.3. and 15.4). Table 15.3 presents the initial values of population stocks and Table 15.4 presents some parameter values used for repetition and dropout rates across age and income groups in year 2000.[9] With these specifications, the model generates synthetic data that allows a direct comparison of simulated PCR (continuous line) to corresponding observed time values (dotted line) from 2000 to 2010, when the last empirical result was published (World Bank, 2015) and period 2010–2050 for forecasting and analysis. Figure 15.4 shows that the model closely replicates real data for the case of Nicaragua.

The bump registered by the simulated PCR in Fig. 15.4 during 2003–2005 occurs as a result of the substantial over/under official age student population accumulated in the educational system during the 1990s coupled with decreasing repetition and dropout rates of the mid-2000s. An educational system with such characteristics can even temporarily overshoot the 100 % completion level when these over/under age students are driven out of the system via higher graduation and/or less dropout and repetition (see Guevara & Posch, 2015). We disaggregated completion rates by income quintile, and simulated them for the period 2000–2015. Thus, this illustration shows Nicaragua as a five-tiered education system. As can be reasonably expected, the first and second quintiles (poorest) are also the worst performers, well below the national average (black thick line) with completion rates under 80 % during the period of analysis, while the top two quintiles are well above the 90 % PCR. The same bump is also observed in Fig. 15.5, particularly at the top quintiles. This result comes in the model's simulation as a consequence of top

[9] Of course the entire data set used to calibrate the model is far larger than that and the one provided in the appendix is just for the sake of illustration. For the complete data set used in the calibration process please contact the authors. Similarly for a detailed description of all assumptions (feedbacks and nonlinear relationships) see Guevara et al. (2014).

Table 15.3 Nicaragua: Population values disaggregated by age and income quintile, circa 2000

Population	Income					
Age	Q1	Q2	Q3	Q4	Q5	Total
0	49,058	47,763	41,961	34,207	14,757	187,746
1	47,794	46,532	40,880	33,326	14,377	182,909
2	46,547	45,318	39,814	32,457	14,002	178,138
3	45,324	44,127	38,767	31,604	13,634	173,455
4	44,131	42,966	37,747	30,772	13,275	168,891
5	42,979	41,844	36,762	29,969	12,928	164,482
6	41,878	40,772	35,820	29,201	12,597	160,268
7	40,838	39,759	34,930	28,475	12,284	156,286
8	39,862	38,809	34,095	27,795	11,991	152,552
9	38,945	37,917	33,311	27,156	11,715	149,043
10	38,069	37,064	32,562	26,545	11,451	145,692
11	37,210	36,227	31,827	25,946	11,193	142,403
12	36,343	35,383	31,085	25,341	10,932	139,084
13	35,451	34,515	30,323	24,719	10,664	135,672
14	34,529	33,617	29,534	24,077	10,387	132,144
15	33,581	32,694	28,723	23,416	10,101	128,516
15>	693,281	674,974	592,990	483,413	208,541	2,653,199
Total	1,345,820	1,310,282	1,151,132	938,417	404,827	5,150,480

Table 15.4 Nicaragua: primary education repetition and dropout parameters, circa 2000

Repetition					
Age	Poorest	II	III	IV	Richest
0	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00
5 or above	0.15	0.12	0.08	0.05	0.00
Dropout					
Age	Poorest	II	III	IV	Richest
0	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00
5 or above	0.05	0.02	0.02	0.00	0.00

income quintiles showing more progress not only in reducing repetition and dropout rates but also in enrolling their children at the official school age. These results are consistent in the country's survey data that show decreasing completion rates in nearly all quintiles after reaching a maximum level, the fifth quintile even over-shooting 100 % (LSMS, 2001, 2005, 2009).

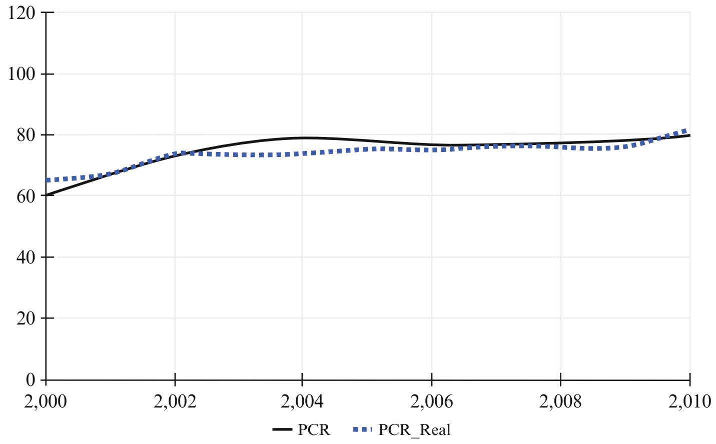

Fig. 15.4 Nicaragua 2000–2010. Simulated (*continuous line*) and observed PCR

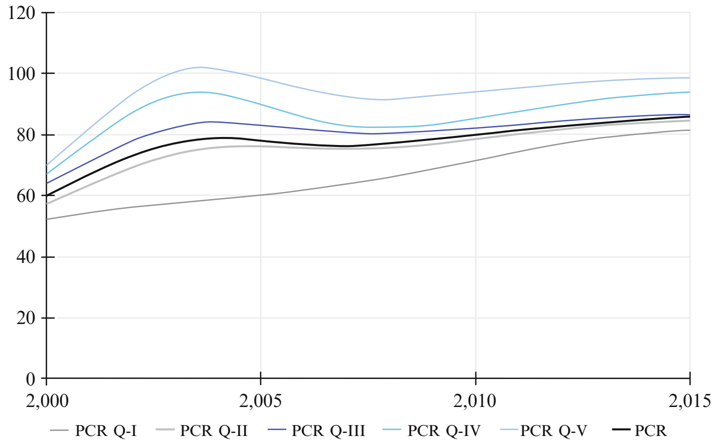

Fig. 15.5 Nicaragua 2000–2015. Simulated primary completion rates by income quintiles

More Scenarios

Note, however, that despite the economic and social differences, students and population in general interact on a more regular basis. Therefore, despite every income quintile being clearly delimited in the Nicaraguan completion rates, these layers are still interdependent as they jointly determine the aggregate amount of literacy in the population which we assume impacts the system's transition rates. The magnitude of these interactions can be better appreciated in results shown by

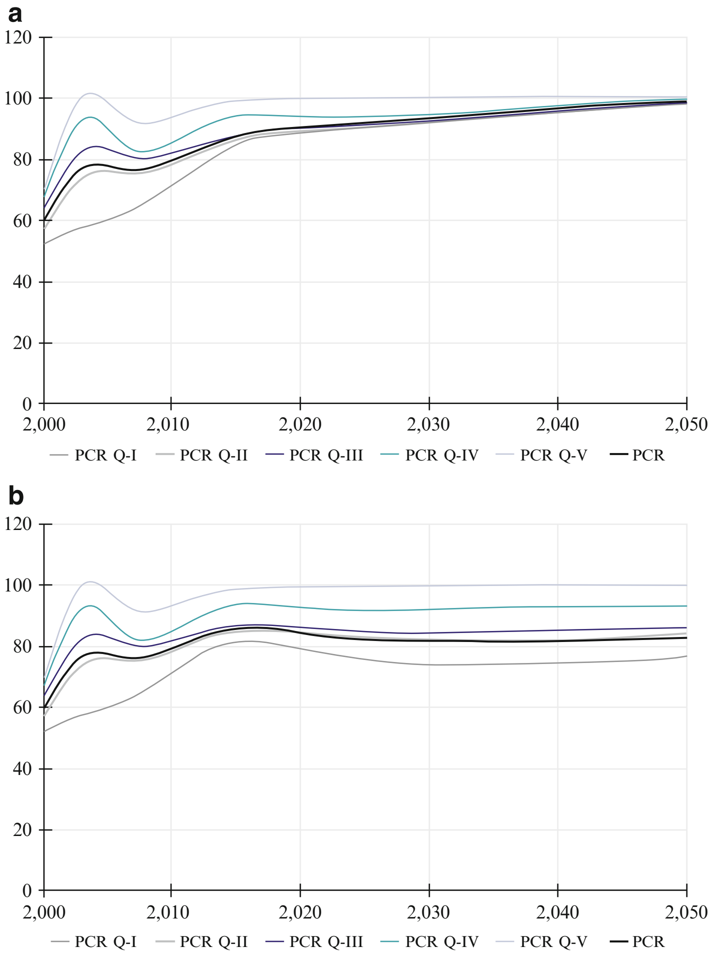

Fig. 15.6 Nicaragua 2000–2050. Simulated completion rates by income quintiles assuming (**a**) economic growth rate of 5 %. (**b**) economic growth rate of 3 %

Fig. 15.6 under two alternative scenarios: one with a strong economic growth and one with a weak economic growth.

In Fig. 15.6a we show that under a strong 5 % economic growth the fifth quintile (the richest) reaches 100 % on its own while the other four quintiles must "wait" until they altogether reach a similar level of completion rate to finally progress toward a maximum completion rate, i.e., the second quintile waits until 2018 for the first quintile to catch up, and similarly the third and fourth wait for the previous ones before advancing in 2020 and 2030, respectively. It also has to do with the fact that the first two quintiles include more than 50 % of the total primary student population and the first four quintiles more than 90 %. On the other hand, assuming a slower economic growth rate of 3 % in Fig. 15.6b,[10] we observe that the first four quintiles primary completion rates do not advance to catch up with the fifth one. Thus, following the patterns generated by the simulations, it is easy to tell that when the overall education system (the black thick line in Figs. 15.5 and 15.6) is below the 80 % threshold and economic growth in the country is not strong, even if one waits for complexities to play out over a long period of time, the system will not eventually converge to 100 % completion level. As GDP per capita is set to be low at the beginning of the simulation for all income quintiles—except the first one—while drop out and repetition rates are very high, income and education will not reinforce each other to fuel completion rates towards its maximum level. A long period of time of robust economic growth would be needed to bring those values of the four lower income quintiles to a level consistent with a full primary completion rate.

Therefore when the whole system has reached a steady-state below the maximum completion rate, policy interventions may be necessary in order to drive it more rapidly toward the higher equilibrium level. The magnitude of these interventions should be adequate to accelerate completion rates—particularly those at the lower income quintiles—up to the point at which the system crosses the lower equilibrium threshold. Once this critical level of 80 % PCR is exceeded, a transition phase occurs via the positive interactions between human capital and economic activity that becomes capable of fueling itself to drive the system to a path of self-sustained momentum until reaching the maximum level. It is at this is point when a society manages to break the clogs-to-clogs cycle at least in primary education.

Discussion

Complex dynamic mechanisms drive many social, economic, and natural processes in modern highly connected societies and the prospects for advancing at the right pace in human development can more likely be accomplished if the impact of past, present, and future events that shape the development paths of countries are identified and understood. But satisfactory answers need consistent models showing alternative paths and the consequences that intertwined factors in human and natural systems may have on the shape and direction of such paths.

In this model, the life opportunities of Nicaraguan children are, at the broadest level, determined by the income, education, and direction they receive from their families which then are reinforced across generations. The stronger and more enriching family environment children receive, the stronger and more enriching family environment they will pass on to the next generation. Using this complex

[10] Here we assume that Nicaragua's population grows at 3 % which means that a 3 % growth in its Gross Domestic Product (GDP) would not change per-capita GDP, which is the ratio of GDP divided by population.

approach we are able to capture several empirical observations about this educational system and project key outcomes into the future.

Complexity modeling and simulation can be regarded as an informed guide for decision-making intelligence providing consistent forecasts when properly designed and constructed. Decision-making intelligence that is timely, relevant, and accurate adds significant value to decision makers when such insights provide consistent information that reduces the uncertainties of future events; this is what a well-designed model should aim to. This in no way is suggesting that models are capable of predicting future events accurately. What it indeed suggests is that in principle all simulated paths should be consistent predictions based on the logic of the model's structure and the impact of the assumed nonlinear relationships. So if the model's logic has been articulated in a consistent way, the model predictions will remain sound, regardless of which particular scenario unfolds, and that provides sound information about the real system. This perspective is likely to lead to a view that the more we learn about the functioning of complex systems using simulation models, the better we will interfere in real-world systems.

As we have already discussed in this chapter, a very useful perspective in demographic education modeling might consider populations as a collection of elements whose combined activities shape the realm of the environment they are embedded in—the behavior of individual components influences the dynamic behavior observed at aggregate level—and the aggregate behavior of that population reciprocally influences individuals' courses of action. We find it particularly interesting to track behavioral patterns generated by segregations stemming from a population whose educational systems—governed by reinforcing feedbacks tend to perpetuate initial conditions—dragging the whole system in poor outcomes due to disadvantaged initial conditions of some segments in the population. When a model's population is disaggregated by income, a much richer collection of behavioral patterns is achieved due to the innate particularities that each income-group possesses regarding enrollment, repetition and dropout. The richest quintiles behave very much like an average developed country with high promotion and low repetition and dropout rates while the first and second quintiles, covering more than 50 % of the population, are more representative of the country reality, showing low completion rates and high repetition and dropout. This, however, has further implications for the educational system as a whole, advancing toward full primary completion at country level becomes increasingly difficult if the poorest quintiles are not brought along with the rich ones, in particular the first quintile. The reason is straightforward and well-recognized in economics; educated people generate positive influence on others to whom they interact with, a concept normally regarded as a positive externality (captured by the model's feedbacks and nonlinear interactions) or in other words the public good nature of equality, in the economic sense of the term. When a sector of the population lacks educational skills such positive externality is interrupted generating a negative effect on their peers (think on the difficulties to transmit ideas efficiently when people lack basic education). All in all, it means that we must turn the impact of these reinforcing feedbacks into an affirmative force that drives high educational accomplishment and better distribution and mobility in society. Even if certain segments of the population—i.e., like the low-income and low-educated—are initially segregated in society, technological advances in communication and transportation make such segments more likely to interact with more educated and affluent ones on a more frequent basis for cultural, social, or economic reasons. So reducing income-based outcomes in educational systems is not just a policy measure to show our solidarity with the most disfavored groups, it is also an effective operational policy required for well-functioning systems. This reasoning thus downplays the premise often argued that inequalities work as an incentive for social mobility implying that at a system level decision makers should not prioritize on policies to level the playing field for all individuals. It is likely that similar results can be obtained with other inequalities like those based on gender, geographical areas, race, etc.

Although the magnitude of intergenerational educational mobility is lower in Nicaragua than in many other countries, the "persistence" pattern derived from reinforcing feedbacks is consistent with low social class mobility in the country and does not differ from the rest of the world. Therefore, we expect that research on the intergenerational transmission of inequality from a complexity system perspective like the one portrayed here can inspire new endeavors to better understand the underpinning of such mechanisms in other countries.

Appendix

The following description of the simulation model is an excerpt from Guevara et al. (2014) reprinted with permission from the journal Nonlinear Dynamics, Psychology, and Life Sciences.

The Simulation Model

The educational model has 3 state variables: Population (P), Population in Primary School (G), and Primary School Graduates (H). These are represented by stocks (rectangles) in Fig. 15.3. P stands for the country's total population, disaggregated into age cohorts and it is the main input to the education system (Eq. 15.1). The arrows in Fig. 15.3 are differential equations that modify the stocks; hence, population increases with births and decreases with deaths. Equation 15.1 shows that the birth rate B, is the product of a constant fractional vector β multiplied by the country's population (i.e., the sum of all age-cohorts). Similarly, death rate D, is the result of a constant ϕ multiplied by the stock of population. In the model, aging $[A(t)]$ represents the transition of the population from one age cohort to the next, after it has remained an average length of time (υ) in that cohort. $P_a(0)$ is the initial population.

$$P_a(t) = \int_{t=t_0}^{T} [B(t) + A_{a-1}(t) - A_a(t) - D_a(t)]\,\mathrm{d}t + P_a(0) \tag{15.1}$$

$$\text{where} \quad B(t) = \beta \sum_a P_a \quad 0 < \beta < 1$$

$$D_a(t) = \phi P_a \quad 0 < \phi < 1$$

$$A_a(t) = {}^{P_a}\!/_{\upsilon} \quad \upsilon = 1,$$

$P_a(t) =$ stock of age-a population, $a = 0, 1, 2, \ldots, 15,$ and Adults (16 or more).

$A_a(t) =$ aging rate, $B(t) =$ birth rate, $D_a(t) =$ death rate,

The second state variable, G, is a matrix broken down by grade and age, encompassing children currently enrolled in school. Equation 15.2 shows that it consists of *6* grades according to the official cycle length in the country. In words, $G_{1,a}(t)$ represents the population of age-*a* students attending the first grade. Once children enter the school system they may follow three mutually exclusive directions: (1) passing to the next level through promotion ($p_{i,a}(t)$) from grade i to $i + 1$ and growing older by 1 year (from a to $a + 1$); (2) repeating the year ($r_{i,a}(t)$) just passing to the next age cohort (from a to $a + 1$) but remaining in the same grade (i); or (3), dropping-out of the grade i at age a ($d_{i,a}(t)$). Note that in Eq. 15.2 intake [$e_{1,a}(t)$] only occurs in the first grade, denominated by $p_{0,a-1}(t)$, and promotion replaces it as an inflow after the second grade. Thus,

$$G_{i,a} = \int_{t=t_0}^{T} \left[p_{i-1,a-1}(t) + r_{i,a-1}(t) - p_{i,a}(t) - d_{i,a}(t) - r_{i,a}(t)\right]\mathrm{d}t + G_{i,a}(0) \tag{15.2}$$

where $G_{i,a}(t) =$ population in grade $i = 1, 2, \ldots, 6$; age $a = 0, 1, 2, \ldots, 15, 16$ (age 16 and above).

$p_{i,a}(t) =$ promotion grade i at age

$e_{1,a}(t) =$ intake rate grade 1 at age a; $p_{0,a-1}(t) \equiv e_a(t)$

$r_{i,a}(t) =$ repetition grade i at age a

$d_{i,a}(t) =$ dropout grade i at age a

All transition rates are specified as the product of a vector of fractions such as intake ($\alpha_{1,a}$), repetition ($\rho_{i,a}$), dropout ($\delta_{i,a}$), and promotion $\left(\pi_{i,a} \equiv \left(1 - \delta_{i,a} - \rho_{i,a}\right)\right)$ multiplied by the stock of people in the respective grade (in the case of intake, by the population stock, P). In addition, these fractional values change across grades but remain constant within grades $\left(\delta_{i,a}, \rho_{i,a}, \pi_{i,a} = \delta_i, \rho_i, \pi_i\right)$. The corresponding formulations are Eqs. 15.3–15.6.

$$e_a(t) = e(P_a(t), \alpha_{1,a}) = \alpha_{1,a} P_a(t) \tag{15.3}$$

$$d_{i,a}(t) = \mathrm{d}(G_{i,a}(t), \delta_{i,a}) = \delta_i G_{i,a}(t) \tag{15.4}$$

$$r_{i,a}(t) = r\left(G_{i,a}(t), \rho_{i,a}\right) = \rho_i G_{i,a}(t) \tag{15.5}$$

$$p_{i,a}(t) = p(G_{i,a}(t), \pi_{i,a}) = \pi_i G_{i,a}(t) \tag{15.6}$$

$$\alpha_{1,a},\ \delta_{i,a},\ \rho_{i,a},\ \pi_{i,a} \in (0,\ 1)\ \text{for every } a$$

The third stock in Fig. 15.3, H, accumulates graduates from primary education as shown in Eq. 15.7. Equation 15.8 describes the construction of an index h of per-capita human capital which is the number of living people who have completed primary school compared to the country's population. This index ranges from 0 to 1 where 0 implies that no adult (i.e., no person aged 16 and above) has completed primary education and 1 means that all adults have at least finished it. Therefore

$$H_{a=16} = \int_{t=t_0}^{T} \left[\sum_a p_{6,a}(t) - D_{a=16}(t) \ \mathrm{d}t \right] + H_{a=16}(0) \tag{15.7}$$

$$h_{a=16} = \frac{H_{a=16}}{P_{a=16}}, \qquad \text{where } 0 \le h \le 1 \tag{15.8}$$

Equations 15.1 to 15.8 allow the construction of the two performance indicators: the gross enrollment rate (from Eqs. 15.1 and 15.2) and the primary completion rate (from Eqs. 15.1 and 15.6):

$$\mathrm{GER} = \sum_{i,a} \frac{G_{i,a}(t)}{P_{7-12}(t)} \tag{15.9}$$

$$\mathrm{PCR} = \sum_a \frac{p_{i,a}(t)}{P_{12}(t)} \tag{15.10}$$

Model Calibration

To calibrate the model it is necessary having a complete dataset for at least one point in time in which all stock variables are disaggregated by age, income group, and level of education attained. In this model that data point corresponds to year 2000 (LSMS 2001, 2005 and World Bank, 2015) and Table 15.3 shows this data point for the population variable used in the model, disaggregated by age and income. Likewise, Table 15.4 presents average parameter values for repetition and dropout rates across all grades for year 2000.

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