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Climate-related Disaster and Human Capital Investment in the Global South — Household Heterogeneity and Growth

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Abstract

This study develops a dynamic model of climate-related disaster impacts, considering multidimensional household heterogeneity, for analyzing changes in growth and inequality in low-income countries. Focusing on human capital development, the study demonstrates the multiple impacts of disaster risk reduction (DRR) policies on human capital investment, including the effect of schooling opportunities for households constrained by the subsistence consumption constraint. Through numerical simulations performed for two economies that differ in terms of human capital, modeled after Madagascar and Fiji, it is illustrated that the possibilities of involuntary unemployment and the work-learning choice drive the diversity in macroeconomic impacts of a disaster. In an economy characterized by low levels of human capital, a disaster could cause an increase in labor supply in the immediate aftermath, but interrupt human capital formation, impeding long-term growth and human capital formation. Such a result contradicts prevailing intuition by demonstrating that a disaster occurring in an economy under recession may not result in a large adverse GDP impact in the short run but may negatively impact growth in the long run. On such a path, a policy of development in DRR infrastructure with appropriate taxation could reduce human-capital gaps in the long run by supporting continued post-disaster human-capital-investment opportunities for the poor.

Keywords: Natural hazards, Economic growth, Household heterogeneity, Human capital investment, Low-income countries

1 Introduction

A catastrophic disaster often leads to the destruction of production factors, thereby resulting in adverse impacts on the short-run macroeconomy, the impacts on long-term growth and inequality remain contested. Although it may be a socially accepted idea that disasters widen the gap between the rich and the poor, empirical evidence remains inconclusive. Moreover, when it comes to modeling the distributional effects of disasters, factors that crucially make the poor more economically vulnerable to disasters have not been clarified as the growth and distributional impacts of a disaster consist of multiple factors that are intertwined, posing significant challenges to sound economic policy analysis.

The aim of this study is to develop a new dynamic macroeconomic model of disasters that allows for assessing growth and distributional implications of disaster impacts and could therefore guide the design of adaptation policy. To that end, the model clarifies the channels through which disasters affect heterogeneous households — expressed in terms of differing endowments of financial assets, human capital, physical household assets, and physical production capital — who interact in real and financial markets. Both the demand and supply sides of the labor market are considered and changes in the human capital gap in society are simulated. The labor market is faced with the possibility of involuntary unemployment and households' elastic labor supply in consideration of time for learning in a school.

In recent years, an increasing number of dynamic models for analyzing impacts of natural hazards and disaster risk reduction (DRR) have been developed. While there are some attempts to develop an integrated modeling framework [e.g., 2], many models are developed based on specific concerns in terms of subjects as variables and market structure. With respect to the former, recent work includes a focus on relationships between different capitals [e.g., 3] and co-benefit of disaster-risk-reduction measures [e.g., 4] while the latter include applications of DSGE models [e.g., 5, 6], disequilibrium

The authors made a presentation at the 28th Annual Conference of the European Association of Environmental and Resource Economists (EAERE 2023) on an earlier-version model [1]. The model is updated for this paper, and the numerical analysis, as well as implications, are completely new, although a large part of the writing of the second section is the same as the conference paper.

models [e.g., 7], Keynesian models with a focus on distribution [e.g., 8], and agent-based models [e.g., 9–11]. The interests and elements that make up this study such as the Keynesian framework, household heterogeneity, and income distribution are each shared with these studies.

This study makes a unique contribution to development of a dynamic model for examining impacts of disaster events and a macroeconomic situation on changes in multi-dimensional household heterogeneity, which is represented by the above-mentioned four stocks as state variables that have different responses either to a disaster or production with one another. For example, we assume the step-function property in the productivity of human capital, which makes its formation process different from that of physical production capital. To the best of our knowledge, it is the first attempt to formulate a model of the four-dimensional household heterogeneity to examine direct and indirect disaster impacts.

Our approach is also unique regarding the extent to which we introduce the optimization. We formulate the household problem by a sequence of the two-period optimization without the recursive relation of dynamic programming. The second-period utility function is defined on a set of the state variables of each household, which is intended to work like a pseudo-value function. Based on such a setting, we can derive closed-form solutions, from which we can interpret the impact of each exogenous variable on its decision-making. On the other hand, numerical simulations are applied to introduce the dynamics of market equilibria and macroeconomic variables: the superposition of household behaviors due to the combination of four-dimensional heterogeneity and various inequality conditions inevitably requires computational work. However, combining the numerical results with interpretation on the analytical stage enables us to understand which impact takes a dominant role in macroeconomic dynamics. With this approach, this study demonstrates four kinds of effects of disaster-risk-reduction (DRR) policy on human capital investment: namely, the income effect, the substitution effect, the choice-opportunity-provision effect, and the externality-reinforcement effect. Moreover, in case studies of two economies, the study illustrates that different effects dominate resulting in qualitatively different observation of long-term growth and distributional consequences between the two countries. Although our results serve to interpret qualitative aspects of macroeconomic dynamics under disaster risks, our approach deals with multi-dimensional heterogeneity that DSGE models cannot handle and derives interpretations that agent-based models cannot clarify.

1.1 Empirical background and motivation

Our modeling motivation is supported by the findings of empirical studies and discussions. As briefly mentioned at the beginning, there is some consensus that natural disasters have a negative impact on macroeconomy in the short run due to human damages, destruction of structures, and so on, which results in slowdowns in production [e.g., 12–14]. On the other hand, the discussion on the long-run effects of natural disasters is inconclusive [e.g., 15]; some studies describe the expansionary disaster effects caused by "creative destruction" [e.g., 16], while others make contrasting conclusions that natural disasters have a negative long-term impact [e.g., 12, 13]. Other results include various assertions including important effects of disasters on growth [17], the lack of partial correlation between natural disaster risk and economic growth [18], different effects across disasters and economic sectors [19], impacts being dependent on political situation [20], greater magnitude of long-term disaster damage in developing societies [21], and the relationship between natural disasters and the poverty trap wherein the poorest households struggle most with shocks [22].

Views on the impact of disasters on inequality are even more varied. Most empirical studies focus on a specific country or region and find, for example, an increase in income inequality in Vietnam [23] and Nepal [24], decreases in Bangladesh [25], Sri Lanka [26], and Myanmar [27]. On the other hand, some studies investigate the issue using cross-country panel data and conclude, for example, a short-term increase in income inequality that disappears over the long run [28], negative relationships between disaster and income inequality in both the short and long run [29], and the vicious cycle wherein countries with higher inequality have a larger number of people affected resulting in further larger inequality [30].

Potential mechanisms are also pointed out. For example, disasters decrease inequality by destroying capital such as buildings and factories which are generally owned by the rich, and infrastructure, the destruction of which thus decreases the productivity of such capital [e.g., 25–27, 31]; disasters decrease inequality of non-agricultural income where wealthier households have a higher share [26]; institutional capacity is an essential factor explaining the link between disasters and distributional impact [32, 33]; humanitarian aid and financial support by the international community after a disaster help explain the reduction in income inequality [34], while such aids could result in moral hazard associated with an increase in inequality [35, 36]. Moreover, households at the bottom of the income distribution lack access to insurance coverage but cope with income shocks by employment of child labor, sale of productive goods [37], changes in both agricultural practices and diet, and out-migration of different length periods [38]. Furthermore, uneven distribution of power and political representation across social groups and across gender also leads to unequal access to prevention and recovery measures, and to financial resources [e.g., 36, 39–42].

As for our special focus on human capital formation in developing countries, many articles have reported detrimental effects of disaster events on education by damaging complementary infrastructure such as school buildings and access roads [e.g., 43, 44]; increasing child work participation rates, which results in the removal of children from schools [e.g., 45–47]; and causing nutritional deficiencies that prevent continuous learning [e.g., 48]. [49] applies cross-country and panel regressions to figure out a robust negative partial correlation between secondary school enrollment and natural disaster risk. While these shed light on the significance of disasters in affecting human capital formation, their broader link to financial and real economy remains unclear. The formulation of a theoretical model, such as the one presented in this study, will help identify key transmission channels.

The rest of this paper is organized as follows: Section 2 formulates the model; Section 3 presents the numerical simulation results; Section 4 discusses implications and future issues; and Section 5 concludes the study.

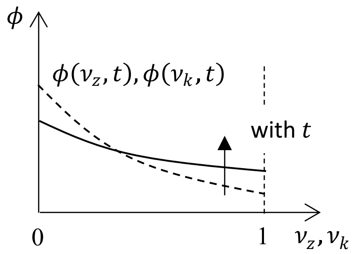


Fig. 1: Density of damage rate

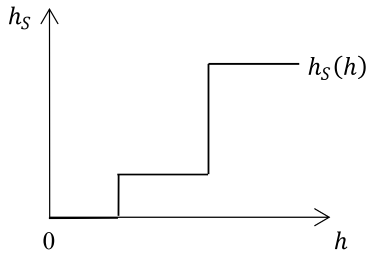


Fig. 2: Classes of human capital

2 Model

2.1 Disaster

A one-sector closed-economy model is formulated. The model is dynamic with a discrete-time horizon. In each period of time t $(= 1, 2, \cdots)$, a disaster arrives with probability λ and destroys a part of physical household assets and production capital, which are damaged by the rates ν_z and ν_k, respectively. While the arrival rate λ is assumed to be constant throughout, the distributions of the damage rates ν_z and ν_k over the interval $[0, 1]$ change over time with climate change. Both arrival and damage rates are independent of previous occurrences. The density functions of the damage rates are given as follows;

$$\phi(\nu_z, t) := \phi_0 \exp(-\phi_1 \nu_z), \tag{1a}$$
$$\phi(\nu_k, t) := \phi_0 \exp(-\phi_1 \nu_k), \tag{1b}$$
$$\text{where} \quad \phi_0 := \phi_1[1 - \exp(-\phi_1)]^{-1}, \tag{1c}$$
$$\phi_1 := \phi_{10} - \phi_{11} t. \tag{1d}$$

ϕ_{10} (> 0) and ϕ_{11} (≥ 0) are constant parameters while ϕ_0 and ϕ_1 change with t so that they meet $\int_0^1 \phi(\nu_z, t) d\nu_z = 1$ and $\int_0^1 \phi(\nu_k, t) d\nu_k = 1$ as illustrated in Fig.1. For simplicity, we assume that ϕ_{10} and ϕ_{11} of the two density functions have the same value. Moreover, all (z, k) owned by heterogeneous households are exposed to the same density functions above in the ex-ante sense, but given different ex-post values by a disaster. The expected damage rates, which are thus equal to the ex-post average damage rates, are given by

$$\begin{aligned} \nu_{zE} &:= \mathrm{E}[\nu_z] = \int_0^1 \nu_z \phi(\nu_z, t)\ d\nu_z \\ &= [\phi_1\{1 - \exp(-\phi_1)\}]^{-1} \{1 - (1 + \phi_1) \exp(-\phi_1)\}, \end{aligned} \tag{2a}$$
$$\nu_{kE} := \mathrm{E}[\nu_k] = \nu_{zE}. \tag{2b}$$

We assume that the disaster damage rates are reduced by the stock of DRR infrastructure D_R by the following factors;

$$\chi_z = \exp\{-\chi_{z1}(D_R - D_{R0})\}, \tag{3a}$$
$$\chi_k = \exp\{-\chi_{k1}(D_R - D_{R0})\}, \tag{3b}$$

where D_{R0} is the initial value of D_R, and χ_{z1} and χ_{k1} are positive parameters. Note that we use the term "disaster risk reduction (DRR)" to indicate "damage reduction" at the time of a disaster, implying that the probability of occurrence of a disaster, λ, is not controlled by DRR policies.

2.2 Household

Households are heterogeneous with respect to four state variables $(a(t), h(t), z(t), k(t))$ where $a(t)$ represents a financial asset, $h(t)$, human capital, $z(t)$, a physical household asset, $k(t)$, physical production capital, and t represents a period of time. Distribution of households in the four-dimensional space $(a(t), h(t), z(t), k(t))$ is represented by the density function $g(a(t), h(t), z(t), k(t))$ that meets

$$\int_a \int_h \int_z \int_k g(a(t), h(t), z(t), k(t)) \; dk \; dz \; dh \; da \quad \equiv 1. \tag{4}$$

Hereafter, we omit the notation "(t)" for brevity as long as we do not need clarification on it. Moreover, we denote the quadruple integral with respect to (a, h, z, k) by the single integral with respect to $\boldsymbol{s} := (a, h, z, k)$, with which expression of the above Eq.(4) is reduced to be $\int g(\boldsymbol{s}) \; d\boldsymbol{s} \equiv 1$, for example. The total population is assumed to be constant throughout and standardized to be unity.

A financial asset a is composed of bond b and money m; namely $a \equiv b + m$. Human capital h is defined by knowledge and skill and is formed by investing time in learning. We define human capital $h(t)$ by a continuous variable, while actual contribution to the productivity of the firm, which we call the class of human capital h_S, is given by a step function: $h_S := h_S(h)$ as illustrated in Fig.2. A reason behind this step-function formulation is supported by several facts that are more often observed in developing countries: (i) the classes that are identified by the graduation of each stage of schooling, for example, are often an observable index based on which jobs or positions are assigned, and (ii) unexpected interruption of learning in the middle of a school stage caused by a large-scale disaster prevents young people from acquiring an organized skill and knowledge at the applicable level. Without such formulation, human capital would become theoretically indifferent to physical production capital, and a model would lose an essential aspect associated with an issue of education disruption caused by a disaster. On the other hand, because we do not consider health and injury in the model although they are one of the factors that compose working capacity in the real world, we assume that human capital is not directly damaged by a disaster. We further assume that human capital investment is conducted by allocating a portion of the time to learning, and is thus associated with a decrease in labor income as an opportunity cost.

A physical household asset z includes dwellings, furniture, and other durable goods that directly bring utility to households who use them. Firms are owned by households by means of physical production capital k. The formation processes of the four state variables are represented as follows;

$$\begin{aligned}
a' &= (1+r)a + \{wh_S \cdot (1-\eta_h)l_D + r_K k_D + \xi\}(1-\phi_\tau) \\
&\quad -\upsilon_\tau - c - Rm - \eta_z z - \eta_k k, &\text{(5a)}\\
h' &= h \cdot (1+\iota\eta_h)(1-\delta_h), &\text{(5b)}\\
z' &= z \cdot (1+\eta_z)(1-\delta_z)(1-\varepsilon_\lambda \nu_z \chi_z), &\text{(5c)}\\
k' &= k \cdot (1+\eta_k)(1-\delta_k)(1-\varepsilon_\lambda \nu_k \chi_k), &\text{(5d)}
\end{aligned}$$

where (a', h', z', k') is the state in the next period. r is the real interest rate, w, the real wage rate, η_h, the human-capital-investment rate, l_D, the employed labor, r_K, the real rate of return to physical production capital, k_D, the employed physical capital, ξ, the firm's profit, ϕ_τ, the income-tax rate, υ_τ, the lumpsum tax, c, consumption, R, the nominal interest rate, η_z, the investment rate of a physical household asset, and η_k, the investment rate of physical production capital. $R = r + \pi_E$ holds by Fisher's equation where π_E is the expected inflation rate of the commodity price, implying that the opportunity cost of holding money is composed of a gain of interest and a decrease in the value of money [e.g., 50]. Moreover, ι is the coefficient of forming of human capital, and $\delta_h, \delta_z, \delta_k$ are the depreciation rates of h, z, k, respectively. ε_λ is the indicator of disaster occurrence; namely, $\varepsilon_\lambda = 0$ if a disaster does not occur in a concerned period, and $\varepsilon_\lambda = 1$ if a disaster occurs.

In each period t, each household focuses on its utility in the current period t and the next period $t+1$ and maximizes the following two-period utility function:

$$U(t) := u_1(\cdot) + \beta u_2(\cdot) \qquad \text{(6a)}$$

where

$$u_1(\cdot) := \gamma_c \frac{(c-\underline{c})^{1-\theta}}{1-\theta} + \gamma_m \frac{m^{1-\theta}}{1-\theta} + \gamma_z \frac{\{z(1+\eta_z)\}^{1-\theta}}{1-\theta} \qquad \text{(6b)}$$

$$\begin{aligned}
u_2(\cdot) := {}& \gamma_a \frac{(a'-\underline{a})^{1-\theta}}{1-\theta} + \gamma_h \left\{1 + \gamma_{hh} \cdot \left(1 - \frac{h_{S+1} - h}{h_{S+1} - h_S}\right)\right\} \cdot \frac{h'^{\,1-\theta}}{1-\theta} \\
&+ \gamma_{zz} \frac{\mathrm{E}[z']^{1-\theta}}{1-\theta} + \gamma_k \frac{\mathrm{E}[k']^{1-\theta}}{1-\theta} \qquad \text{(6c)}
\end{aligned}$$

$u_1(\cdot)$ is the sub-utility function of the variables in the current period, and $u_2(\cdot)$ is one of the variables in the next period. β $(0 \leq \beta \leq 1)$ is a discount factor, and θ is a degree of relative risk aversion. $\gamma_c, \gamma_m, \gamma_z, \gamma_a, \gamma_h, \gamma_{hh}, \gamma_{zz}, \gamma_k$ are positive parameters that determine weights of the terms. In the current-period utility function defined by Eq. (6b), $\underline{c}$ (≥ 0) is the subsistence consumption which means in this model the minimum basic needs of life [e.g., 51]. The money-in-utility form [52] is applied to easily derive the demand function for money. We assume that households can enjoy the level $z(1+\eta_z)$ of a household asset in the current period before it gets depreciated. The next-period utility function defined by Eq.(6c) is composed of the state variables in the next period. $\underline{a}$ (< 0) is the lowest level of the financial asset that is introduced for the technical reason of making $(a' - \underline{a})$ always positive, considering that a' itself could be negative when a household takes a negative position of a bond. The second term related to the utility of h' includes the motivation for the human capital investment where the closer h is to the next class h_{S+1}, the more strongly a household is motivated to continue learning. $\mathrm{E}[z']$ and $\mathrm{E}[k']$ are the expected levels of a household asset and physical capital, respectively, that are given by

$$\mathrm{E}[z'] = z \cdot (1 + \eta_z)(1 - \delta_z)(1 - \lambda \cdot \nu_{zE} \cdot \chi_z), \tag{7a}$$

$$\mathrm{E}[k'] = k \cdot (1 + \eta_k)(1 - \delta_k)(1 - \lambda \cdot \nu_{kE} \cdot \chi_k). \tag{7b}$$

While we do not apply the recursive framework of dynamic programming, the next-period utility function, which is assumed to be the isoelastic function of the next-period state variables, is intended to reflect a part of the properties of a value function, thus may work as a pseudo-value function[1].

We assume that households are faced with the borrowing constraint:

$$b(t) \geq b_{\mathrm{Lim}} \quad \text{for any } t \tag{8}$$

where b_{Lim} is the borrowing limit that meets $-\infty < b_{\mathrm{Lim}} < 0$ [e.g., 53]. From the identity $a \equiv b + m$, demand for money in Period t is constrained by the following area:

$$0 \leq m(t) \leq a(t) - b_{\mathrm{Lim}}. \tag{9}$$

The household problem is represented as follows:

$$\max_{c, m, \eta_h, \eta_z, \eta_k, a'} U(\cdot) \tag{10a}$$

$$\text{subject to} \quad 0 \leq \eta_h \leq 1, \ \eta_z \geq -1, \ \eta_k \geq -1, \tag{10b}$$

$$\text{Eqs. (5a)-(5d), (7a), (7b), (9).}$$

The inequality constraints in Eq.(10b) imply that the total available time in each period is standardized to be one, and η_h is equivalent to the time for learning in that period. Moreover, a household can also sell a part of its physical household asset and physical production capital by choosing η_z and η_k in the area $-1 \leq \eta_z, \eta_k \leq 0$, respectively. Due to the inequality constraints that may lead to corner point solutions, there are multiple patterns of optimal solutions. Among them, the typical case of interior point solutions is shown in Appendix A.

[1] The genuine value function is a function that is also defined by other variables that affect market prices, such as the total stock of each state variable in the economy and the level of DRR infrastructure. We avoid directly incorporating those variables in defining the next-period utility function, while the solutions will reflect the market prices as shown in Appendix A.

2.3 Firm

Firms are homogeneous and have constant returns-to-scale technology with respect to labor and capital:

$$F(L_D(t), K_D(t), A(t)) := A(t)\{\alpha_L L_D(t)^\rho + \alpha_K K_D(t)^\rho\}^{\frac{1}{\rho}} \tag{11}$$

where $L_D(t)$ and $K_D(t)$ represent labor and capital demands, respectively. $A(t)$ is the total factor productivity that increases by the exogenous rate g_A. The notation of $A(t)$ in the parentheses of $F(\cdot)$ is omitted hereafter. α_L, α_K, and ρ are parameters that are constant throughout. The labor is measured in terms of the effective labor unit that is defined by the product of human capital and working time.

Labor and physical capital supplies are given respectively by the following:

$$\bar{L}(t) := \sum_{S=1}^{S_M} h_S \int_S^{S+1} \{1 - \eta_h(\boldsymbol{s})\} g(\boldsymbol{s}) d\boldsymbol{s} \tag{12a}$$

$$\bar{K}(t) := \int_0^\infty k(\boldsymbol{s})\ g(\boldsymbol{s}) d\boldsymbol{s} \tag{12b}$$

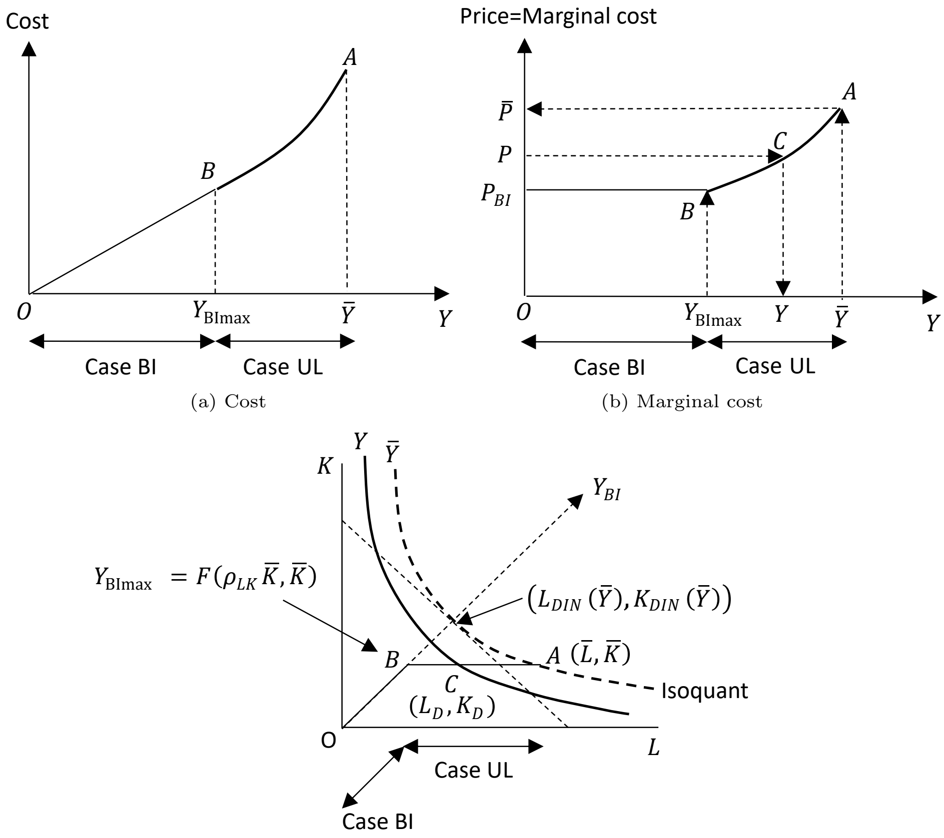
where the low-case variables k and η_h represent the levels of one household of the state $\boldsymbol{s}$. It is assumed that $h_1 = 0$ and $h_{S_M+1} = \infty$. $\{1 - \eta_h(\boldsymbol{s})\}$ is a time for working, whose value is determined by each household.

We assume that the factor prices are sticky, and as of the beginning of Period t, the Period-t factor prices are already determined. Hence, the factor markets are closed by the quantity adjustment and associated with unemployment although the production technology is represented by the homogeneous function of degree one with respect to labor and physical capital. Figure 3 illustrates a case of unemployment of labor. Suppose $\bar{Y} := F(\bar{L}, \bar{K})$ is the full-employment production level. Because the representative firm determines the level of production Y so that its marginal cost is equalized with commodity price P, it can happen that $Y < \bar{Y}$ that is associated with $L_D < \bar{L}$. Moreover, depending on the provided (W, R_K) and Y, the input bundle (L, K) is not necessarily the interior point solution of the cost-minimizing problem; Case BI (balanced inputs) in Fig.3 indicates a case where the factor demands (L_D, K_D) are given by the interior point solution represented by $(L_{DIN}(Y), K_{DIN}(Y))$ derived in the problem:

$$\min_{L_D, K_D} WL_D + R_K K_D \tag{13a}$$

$$\text{subject to} \quad F(L_D, K_D) = Y, \tag{13b}$$

while Case UL (unemployment of labor) applies if $K_{DIN}(Y)$ exceeds the stock $\bar{K}(t)$ (equivalently, $Y > Y_{\text{BImax}}$): the demand for labor is determined at Point C in the interval AB in Fig. 3c, namely in the area $\rho_{LK}\bar{K} := L_{DIN}(Y_{\text{BImax}}) < L_D < \bar{L}$, where $\bar{L} - L_D$ is not employed and the marginal cost of production is increasing (Figs. 3a, 3b). Case UK (unemployment of capital) can occur in the same manner. The firm's



(a) Cost

(b) Marginal cost

(c) Inputs

Fig. 3: Input and output for production

profit is derived as

$$\xi := PY - (WL_D + R_K K_D). \tag{14}$$

2.4 Government

Money is supplied based on the increase rate of money, which meets

$$\mu \equiv \frac{M_S(t+1) - M_S(t)}{M_S(t)}, \tag{15}$$

where $M_S(t)$ represents the nominal money supply. μ is assumed to be constant. The government invests in DRR infrastructure D_R that develops by

$$D_R(t+1) = (1 - \delta_D)D_R(t) + \zeta(t), \tag{16}$$

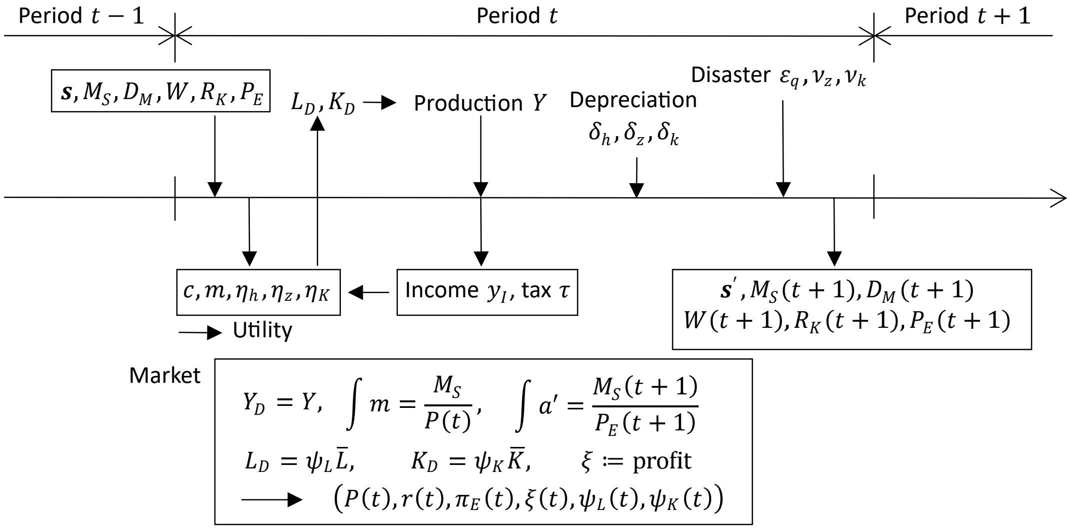


Fig. 4: Event sequence

where $\zeta(t)$ represents the investment, which is financed by seignorage and tax, namely

$$\zeta(t) = \mu \frac{M_S(t)}{P(t)} + \int \tau \; g(\boldsymbol{s}) d\boldsymbol{s} \tag{17a}$$

$$\text{where} \quad \tau := \phi_\tau \{ w h_S \cdot (1-\eta_h) l_D + r_K k_D + \xi \} + \upsilon_\tau \tag{17b}$$

and ϕ_τ and υ_τ are the income-tax rates and the lumpsum tax, respectively, and are assumed to be constant. We assume that there is no other government's consumption and investment.

2.5 Market

The factor-price markets are assumed to be sluggish. We assume that the increase rates of the nominal wage rate and the nominal return rate of physical capital are given by

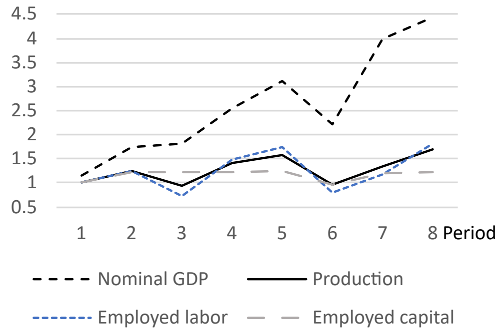
$$\frac{W(t+1) - W(t)}{W(t)} \equiv \pi_W(t) := \mu + \kappa_W \cdot \left\{ \frac{\bar{L}_D(t)}{\bar{L}(t)} - 1 \right\}, \tag{18a}$$

$$\frac{R_K(t+1) - R_K(t)}{R_K(t)} \equiv \pi_{RK}(t) := \mu + \kappa_{RK} \cdot \left\{ \frac{\bar{K}_D(t)}{\bar{K}(t)} - 1 \right\}, \tag{18b}$$

$$\text{where} \quad \bar{L}_D(t) := \max[L_D(t), L_{DIN}(Y(t))], \tag{18c}$$

$$\bar{K}_D(t) := \max[K_D(t), K_{DIN}(Y(t))], \tag{18d}$$

and μ is the increase rate of the money supply. κ_W and κ_{RK} are parameters of the non-negative values that reflect the speed of the price adjustment. It is implied that, in the case of the unemployment of labor in Period t, where $\bar{L}(t) > L_D(t) > L_{DIN}(Y(t))$ and $\bar{K}(t) = K_D(t) < K_{DIN}(Y(t))$ as illustrated in Fig.3c, the nominal wage rate (rate



- The values of production, employed labor, and employed capital of each period are expressed as a ratio to their initial values.

Fig. 5: Nominal GDP, production and employment (Case 0, Country M)

of return to physical capital) increased by the rate that is smaller (larger) than the rate of an increase in the money supply.

Figure 4 illustrates the sequence that variables are determined. We assume that disaster randomly arrives at the end of each period, therefore, direct impacts of the period-t disaster appear in the decrease in z and k in Period $t+1$. We further assume that, due to the timing of a disaster, a realized value of the commodity price $P(t)$ and the expected inflation rates are related in the following manner:

$$P_E(t) = \{1 + \pi_E(t-1)\} \cdot P(t-1), \tag{19a}$$

$$P(t) = \{1 + \varepsilon_P(t)\} \cdot P_E(t). \tag{19b}$$

$P_E(t)$ represents the expected price that is obtained based on the expected inflation rate in Period $t-1$. Realized price $P(t)$ generally differs from $P_E(t)$ after the realization of stochastic factors related to a disaster. The market closure is given by a set of the following equations:

$$Y_D := \int \{c(\boldsymbol{s}) + \eta_z(\boldsymbol{s})z + \eta_k(\boldsymbol{s})k\}\ g(\boldsymbol{s})d\boldsymbol{s} + \zeta = Y, \tag{20a}$$

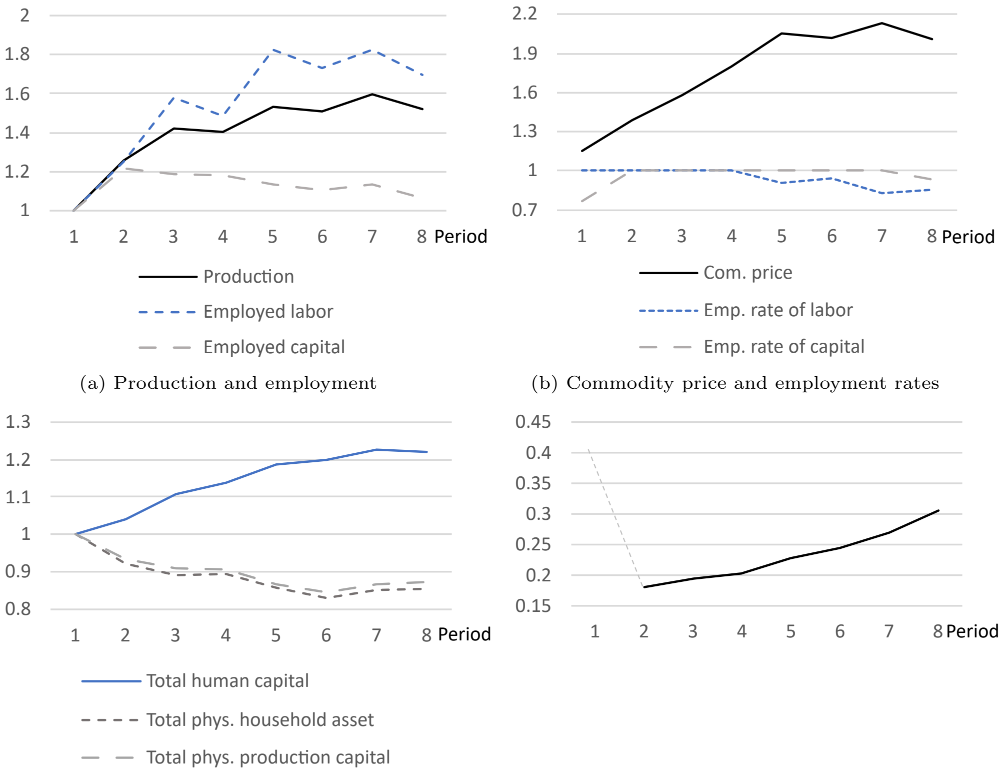
$$\int m(\boldsymbol{s})\ g(\boldsymbol{s})d\boldsymbol{s} = \frac{M_S}{P}, \tag{20b}$$

$$\int a'(\boldsymbol{s})\ g(\boldsymbol{s})d\boldsymbol{s} = \frac{M_S(t+1)}{P_E(t+1)}, \tag{20c}$$

$$L_D = \psi_L \bar{L}, \tag{20d}$$

$$K_D = \psi_K \bar{K}, \tag{20e}$$

and Eq.(14) that defines the profit ξ. From the six conditions, $(P, r, \pi_E, \xi, \psi_L, \psi_K)$ are determined. The bond market is not independent and automatically closed. Eq.(20c) is derived from $\int b' = 0$, $b' = a' - m'$, and $\int m' = M_S(t+1)/P_E(t+1)$.



(a) Production and employment

(b) Commodity price and employment rates

(c) Total stocks

(d) Gini coefficient of income

- The values of production, employed labor, and employed capital (Fig. a), total human capital, total physical household asset, and total physical production capital (Fig.c) of each period are expressed as a ratio to their initial values.

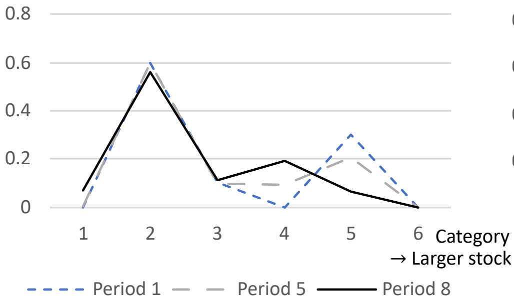
Fig. 6: Process of macroeconomic variables (Case 1, Country M)

3 Numerical example

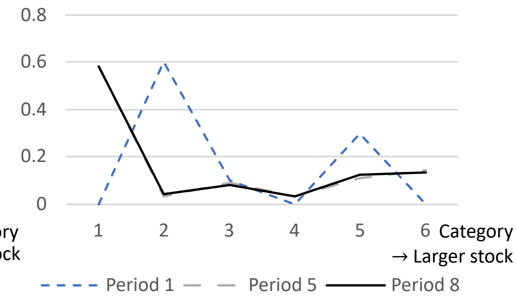
3.1 Two-case-economy setups

To examine core model behaviors, this section simulates two numerical cases of hazard-prone island economies with varying levels of heterogeneous asset endowments, namely "Country M" and "Country F" by specifying the values of parameters and initial states from data from Madagascar and Fiji, respectively.

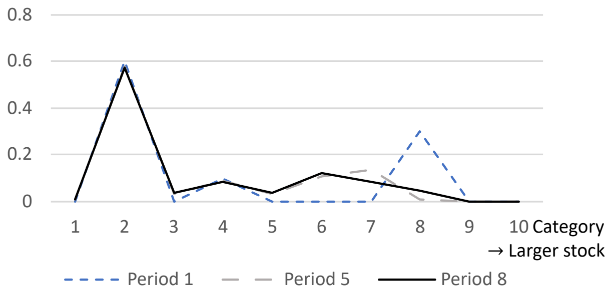
Madagascar is a low-income country with a GDP per capita ranked 182nd in the list of 190 IMF-member countries in 2023 [54] and a 0.43 Gini coefficient of income in 2012 [55]. Other indications of low socioeconomic development include mean years of schooling (4.90 in 2020) where 53% of the population belongs to the classes of "No Education" or "Incomplete Primary" [56] (Table B3). Educational attainment is frequently focused on as a proxy of human capital. There is some indication however that progress has been made on this front with 4.47 mean years of schooling in 2015,



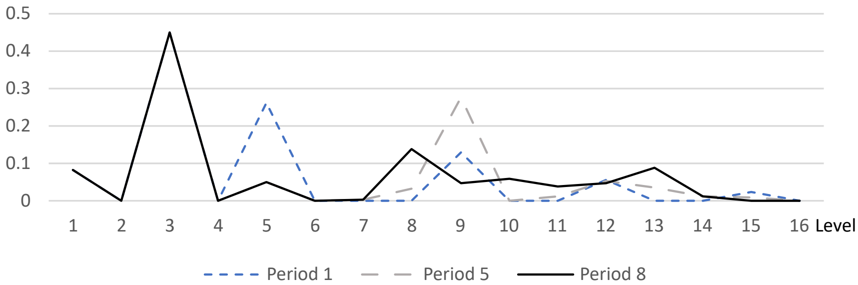
(a) Marginal density: financial assets



(b) Marginal density: physical household assets



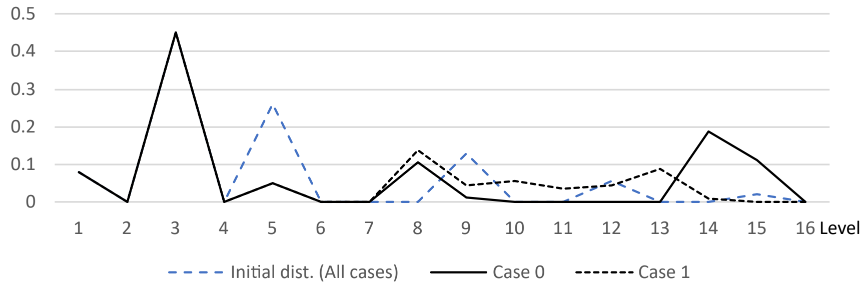
(c) Marginal density: physical production capital



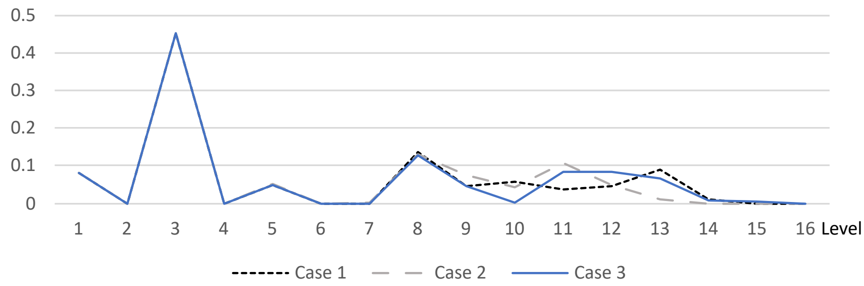
(d) Marginal density: human capital

- Changes in the distribution of the households' state variables $g(a, h, z, k)$ are represented by the marginal distribution in terms of the values of the marginal density function. The horizontal axes represent categorized levels of the stocks and indicate that the stocks are larger in higher categories. While disparities of financial assets a and physical production capital k among households narrow over time, that of physical household assets z becomes polarized. (Figs.a-c)
- Each level of human capital is defined by the schooling year; for example, Level 5 corresponds to the state where an individual graduates from a primary school where pupils learn for five years in the Madagascar school system. We assume that individuals with "No Education" and "Incomplete Primary" in the initial period in the data are indicated by Level 1 and Level 3, respectively. (Fig.d)
- In case multiple density curves overlap, the curve for the earlier period is hidden behind the curve for the later period. For example, the curve of z of Period 5, which almost overlaps the curve of Period 8, exists behind it. The curve of h of Period 5 exists behind that of Period 8 over the interval between Levels 1-7. (Fig.d)

Fig. 7: Change in distribution of household heterogeneity (Case 1, Country M)



(a) Marginal density of human capital in Period 8 (Cases 0, 1)



(b) Marginal density of human capital in Period 8 (Cases 1, 2, 3)

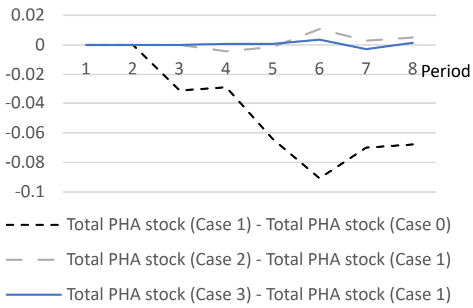
- Level corresponds to years of schooling.
- In case multiple density curves overlap, the curve for the smaller case number is hidden behind the curve for the larger case number. Over the interval between Levels 1-4, all the curves overlap.

Fig. 8: Marginal density of human capital in Period 8 (Country M)

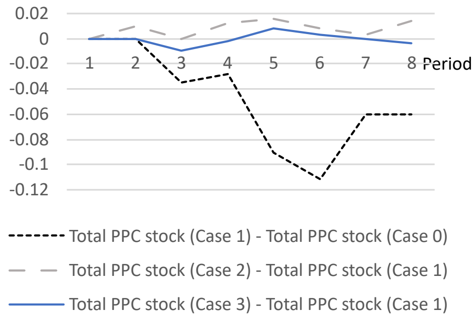
implying a nearly 10%-increase in five years and potentially a continued trajectory toward a greater level of educational achievement in the future.

Fiji's GDP per capita ranks 99th among the IMF member countries in 2023 [54]. The Gini coefficient of income decreased from 0.40 to 0.31 between 2008 and 2019 [55]. The average years of schooling are 14.58 years as of 2017 [57], which is higher than "Graduated Secondary (12 years)" and even "Graduated Diploma (14 years)" in the Fijian education system [58]. Fiji is clearly a different country from Madagascar in terms of human capital stock. However, here, unlike in the case of Madagascar, data on the distribution of years of schooling do not exist.

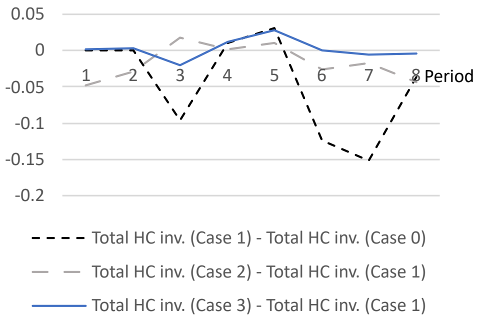
The set of parameter values used in this example is listed in the tables in Appendix B. Note that some data pertaining to parameters, initial stocks, and their distributions are not available. We assumed some and estimated others by calibration so that GDP, the Gini coefficient of income, the total stock of each variable, and so on in the base year are reproduced. These assumptions may directly affect nonlinear dynamic behaviors such as oscillations. Therefore, this numerical example is not intended to predict the future of Madagascar and Fiji with a high degree of accuracy, but, by setting up virtual Countries M and F, to obtain from the results a qualitative understanding of some



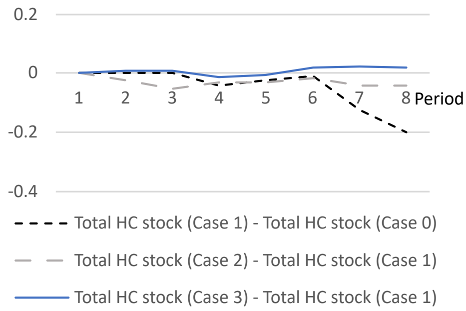
(a) Difference in total stock of physical household asset



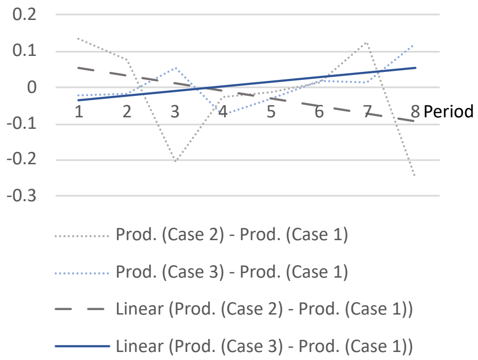
(b) Difference in total stock of physical production capital



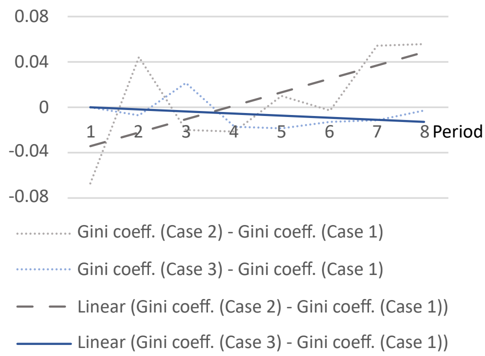
(c) Difference in total investment in human capital



(d) Difference in total stock of human capital



(e) Difference in production



(f) Difference in Gini coefficient of income

- The values of total physical household assets (Fig. a), total physical production capital (Fig. b), and total human capital (Fig. d) of each period are expressed as a ratio to their initial value.
- The values of total human capital investment of each period are expressed as a ratio to the initial stock of human capital (Fig. c).
- The values of production are expressed as a ratio to the initial value of Case 0 (Fig. e).
- The lines indicated by "Linear" represent linear regression lines.

Fig. 9: Impacts of disasters and disaster policies (Country M)

essential aspects of the dynamics that can occur in a developing society with similar attributes such as Madagascar's and Fiji's, respectively.

We compare four scenarios — namely baseline of no disaster, no DRR investment (Case 0), disasters only (Case 1) disasters and DRR investment financed via a flat tax rate (Case 2), and disasters and DRR investment financed via progressive taxation (Case 3).

3.2 Case of "Country M"

3.2.1 Disasters and human capital formation

We observe the non-monotonic process of production resulting from the non-linear factors such as the money-demand function, human-capital-investment function, and the aggregation of heterogeneous behaviors of households (Fig.5). Even in the absence of disasters, the production level (equivalent to real GDP) drops in Periods 3 and 6[2]. When disasters occur at the end of Periods 2, 4, and 5 in Case 1, the production levels increase in Periods 3, 6, and 7 due to the reconstruction demand (Figs.5, 6a). It is important to note that such increases are significantly large during recessions namely Periods 3 and 6. The economy goes under inflationary pressure in the first four periods and the price level later fluctuates (Fig.6b). From Period 2 onwards the Gini coefficient of income continues to increase, being dominated by the expansion of the human capital gap (Fig.6d)[3].

The distribution of human capital h is shown in Fig.7d. The comparison of the distribution of the final period for Case 0 and Case 1 shows that the occurrence of disasters hinders the development of human capital (Fig.8a). In Periods 3, 6, and 7 when post-disaster reconstruction demand increases, this increase in output comes at the expense of human capital investment due to a subsistence constraint.

3.2.2 Effects of DRR investment under alternative tax regimes

Cases 2 and 3 illustrate complex channels through which DRR investments financed under alternative tax regimes affect long-run growth and distributional consequences. Figure 9 compares Case 3 (i.e., DRR with progressive tax) with Case 1 (i.e., disasters only), which indicates that physical household assets and physical production capital stock do not increase from that of Case 1 despite the decreased disaster damage (Figs. 9a, 9b). Such results suggest that DRR investment may have a crowding-out(-like) effect on investment in physical production capital. This is because of the higher tax burden placed, especially on the wealthier households who would otherwise take a central role in investing in the total stock of physical production capital. Given the flat taxation of Case 2 mitigates their tax burden, such effect disappears in Fig.9b.

[2]Note that, for ease of illustration, the levels of production, employed labor, and employed capital in each period in the figure are expressed as a ratio to their values in Period 1, with units eliminated. The levels of Nominal GDP are given by the product of the standardized production and the commodity price. The value of production in Period 1 of Case 0 will be used to standardize values of production in subsequent cases. In this section, we apply the standardization in figures also for the total stocks of human capital, physical household assets, and physical production capital, using their respective initial values.

[3]The incomplete data causes the adjustment process observed for the initial period by necessity only, and thus our analysis focuses on the impacts from Period 2 onwards.

However, the Case 2 scheme, where DRR investment is financed through a flat tax rate, does not encourage human capital formation, especially for those in the middle categories (i.e., between Level 5 "Complete Primary" and Level 8 in the initial period) (Fig.8b). These households instead are more strongly motivated to increase labor income in order to raise the current consumption; in other words, the income effect dominates against the substitution effect. The total human capital stock is decreased in Case 2 from Case 1 (Fig.9d). The progressive taxation of Case 3, on the other hand, encourages greater education, resulting in the development of the total human capital (Fig.9d) and the decrease in the human capital gap between the middle-human-capital class and the high-human-capital class (i.e., Larger than Level 9 "Complete Junior Secondary" in the initial period) (Fig.8b).

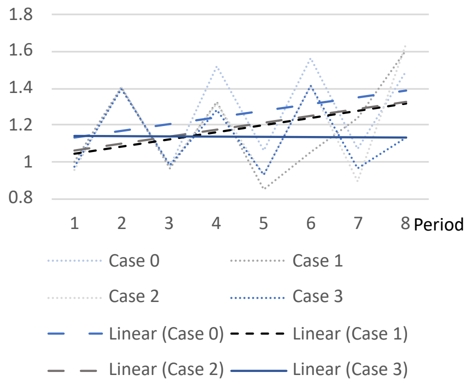
Overall, DRR investment under the progressive taxation performs better in terms of growth and inequality. At the same time, it must be emphasized that such policy is still insufficient to encourage those households, with little or no education, to invest in human capital formation (Fig.8). These households remain trapped at their initial level of human capital endowment, and the human capital gap between them and those of the middle-human-capital class widens over time. Complementary policy beyond DRR will be needed to address such low-human-capital-trap issues.

3.3 Case of "Country F"

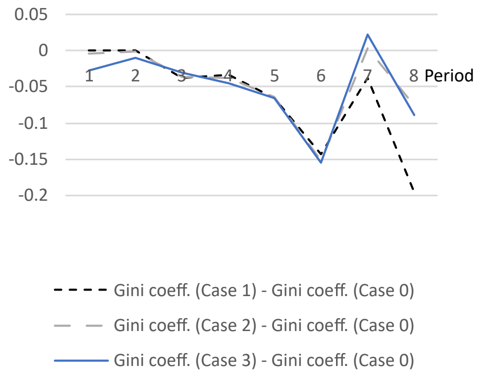
As in the setting of Country M, disasters occur at the end of Periods 2, 4, and 5. Periods 3, 5, and 6 are the periods immediately following the disaster. Our results focus on those aspects that are qualitatively different from Country M. Comparing Cases 0 and 1 in Fig.10a, the production levels in the immediate aftermath of a disaster in Case 1 are smaller than in Case 0. This is caused by the direct and indirect effects of disaster damage on physical production capital. The direct impact is due to the reduction in capital as a factor of production. The indirect impact is due to a decrease in the demand for labor through a decrease in the marginal productivity of labor. This decrease in labor demand leads to a decrease in labor supply by households in anticipation of it and an increase in their learning time. The level of human capital is thus highest in Case 1, which has the highest disaster damage (Fig.10d), while Case 0, with no disaster damage, has the lowest human capital level. As a flip side to this, the level of physical production capital is highest in Cases 0, followed by Cases 2, 3, and 1 in Period 8 (Fig.10c). In Country F, the human capital gap in the final period is smallest in Case 1, as a human capital investment of households in the lower-human-capital class is encouraged (Fig.8). Reflecting this, the order of the smallest Gini coefficient of income is also roughly consistent with the order of the largest human capital levels (Fig.10b).

Such prominent behaviors regarding the human capital investment in the aftermath of a disaster in Case 1 are reflected also in the production path. While the production process shows a regular cycle in Cases 0, 2, and 3[4], in Case 1, production increases in Period 7 more than in Period 6 (Fig.10a). This is because production declines in the

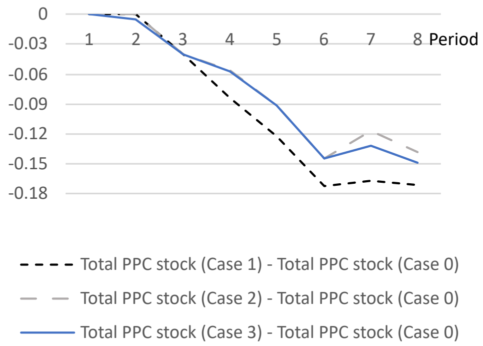
[4]While there are nonlinear factors in this model that often lead to business cycles, oscillations could also be caused simply by discretization of the time horizon. Since such a possibility cannot be ruled out, we do not discuss business cycle issues here and limit our focus to the fact that in Case 1, production in Period 7 is higher than in Period 6 due to the lagged reconstruction demand. In contrast, Cases 2 and 3 present



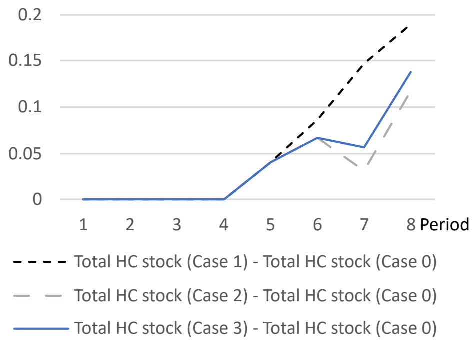
(a) Production



(b) Difference in Gini coefficients of income



(c) Difference in total stock in physical production capital



(d) Difference in total stock of human capital

- The values of production are expressed as a ratio to the initial value of Case 0. (Fig. a)
- The lines indicated by "Linear" represent linear regression lines.
- The values of total physical production capital (Fig. c) and total human capital (Fig. d) of each period are expressed as a ratio to their initial value.

Fig. 10: Impacts of disasters and disaster policies (Country F)

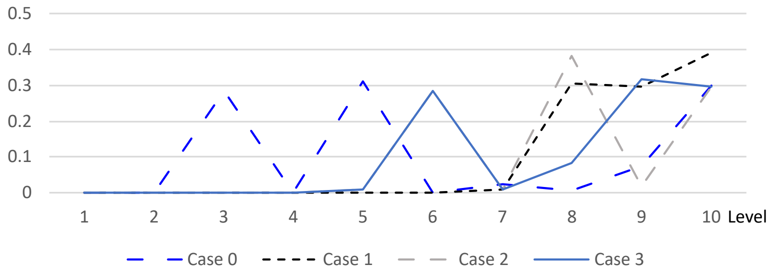
immediate aftermath of a disaster (Periods 5 and 6) but the reconstruction demand is generated after Period 7 when productive capital is beginning to be restored.

4 Discussion

4.1 Characteristics of the model framework

The model of this study is a monetary dynamic equilibrium model that takes unemployment into account, and in this respect, it has similar components to DSGE models. However, DSGE models can handle dynamic optimization problems with infinite horizons, although they cannot analyze the market equilibrium of households with

the same cycle as Case 0 in Period 7 because of the decreased reconstruction demand due to the reduced damage.



- Level 1 corresponds to 11 years of schooling, and Level 10, to 20 years.
- In case multiple density curves overlap, the curve for the smaller case number is hidden behind the curve for the larger case number. The curves for Cases 1-3 overlap in the Levels 1-4 interval, and the curves for Cases 2 and 3 overlap in the Levels 5-7 interval.

Fig. 11: Marginal density of human capital in Period 8 (Country F)

multi-dimensional heterogeneity. Changes in household heterogeneity and inequality under risk have been of interest in research categories such as (i) empirical analysis, (ii) conceptual models for theoretical analysis, and (iii) agent-based models (ABM). Those frameworks and the approach of this study differ in the following features.

(i) Empirical studies are best at understanding the details brought by actual disaster events. On the other hand, there are limitations in the scope of using estimated parameters to predict future dynamics; in particular, the interactions among agents through price changes and the non-monotonic changes of aggregate quantities, which are of interest to this study.

(ii) There are also models such as mean-field games that analytically analyze the dynamics of a continuous distribution of heterogeneous households [e.g., 59, 60]. There, elaborate theoretical analysis is performed, but the number of equations and state variables is limited. In contrast, this model is characterized by its ability to incorporate situations in which multidimensional stocks are distributed even discontinuously, to handle various combinations of inequality constraints, and to compute the dynamics resulting from the superposition of those results.

(iii) ABMs deal with a huge number of variables and heterogeneities in many cases. Or, with a small number of variables and heterogeneities, such models present a complex system. ABMs often do not allow us to understand from the simulation results the chain of effects and causal relationships among variables. In this study, the size of the model is kept to the extent that they can be accounted for.

The model of this study is located between a dynamic optimization model and ABM and is associated with the following intentions.

(a) By employing the two-period optimization problem under uncertainty, the solution retains a certain level of being normative. The second-period utility function in the objective function is not a value function that is endogenously determined in a recursive framework but an exogenously given function, but it is highly tractable. We developed techniques such as incorporating in this formulation both risk aversion and post-disaster recovery motives in physical asset formation behavior.

(b) The numerical analysis provides a qualitative understanding of household behaviors and interactions and the non-monotonic process of macro variables. As will be concretely described in 4.2, the framework allows us to list multiple sorts of potential DRR effects, and it is figured out from the numerical simulation what interactions are taking place and which effects are dominant depending on the environment of a parameter set.

(c) The case study, which includes multiple assumptions on the parameter values, is not aimed at predicting the future of Madagascar and Fiji with high accuracy. Still, it is more significant than numerical examples performed with a completely hypothetical country setting. In other words, because of a potentially large variety of nonlinear dynamics the model exhibits and of a huge number of possible combinations of the model parameters, it is critically important to specify a subset of the entire parameter space at an area close to a realistic one. We thus set up Countries M and F that represent two distinct typical environments in the Global South. As will be discussed in 4.3, the result implies that, even within the Global South, different country types may have qualitatively very different expectations about the long-term impacts of disasters, as well as different policies required for disaster reduction and taxation. Analysis using this model can contribute to categorizing policy and aid patterns, determining which pattern the country of interest belongs to, and discussing policy directions.

4.2 Impacts of a disaster event and disaster risk reduction on human capital development

Our simulation results indicate that post-disaster human capital allocation is a key factor determining the immediate and longer-term outcome of disaster recovery in Global South countries. Household labor/educational time allocation is mediated by factors including the need for subsistence consumption, post-disaster labor productivity, and borrowing constraints. In general, catastrophic disasters force working-age youth to allocate more time for labor, instead of study, when the economy is operating at the near or below subsistence level as in Country M. Such tendency, while attenuating the short-run adverse impacts on GDP, traps labor into lower productivity thereby compromising growth prospects in the longer-term. In fact, under the subsistence constraint, the popularized notion that "a disaster leads to short-run adverse consequences on GDP" may not hold true, and adverse impacts may manifest with a significant time lag. In contrast, in Country F, the subsistence-consumption condition is non-binding, allowing households in low-income groups to continue schooling. Disasters hence have regressive effects across countries with respect to human capital formation.

We found that human-capital-investment behavior is further mediated by pecuniary externalities among households. When labor supply, measured in efficient labor units, is increased by households of the high-human-capital group, this lowers the wage rate (per efficient labor unit) for all households. This affects households in the low-human-capital group in two possible ways: when the subsistence consumption constraint is non-binding as seen in Country F, it reduces the opportunity cost of learning (i.e., human capital investment) thereby encouraging human capital investment. However, if the decline in income makes the subsistence-consumption constraint binding, households will be forced to reallocate time away from learning to labor.

We further find that DRR policy on human capital investment can be summarized by the following four effects: (i) the income effect, (ii) the substitution effect, (iii) the choice-opportunity-provision effect, and (iv) the externality-reinforcement effect, which are elaborated in Appendix A.

The income effect refers to the extent to which DRR investment by the government reduces disaster damages to physical assets and production capital, thereby changing income and in turn investment (in various assets including human capital) and consumption. The exact extent of the income effect varies depending on the employment level and other factors, as an increase in production capital realized via DRR investment does not automatically translate to an increase in production and household income. It is also important to note that the taxation for financing of DRR investment reduces disposable income and hence is a key consideration for the distributional consequences.

The substitution effect refers to the extent to which DRR investment decreases the expected damage rates of physical household assets and physical production capital, thus increasing their investment efficiency, which raises the relative effective price of human capital investment. DRR policy hence works to reduce human capital investment.

The choice-opportunity-provision effect may be considered part of the income effect but is uniquely related to the inequality constraint regarding the subsistence consumption. As seen in Country M, a household may be facing a binding subsistence-consumption constraint in case of a disaster that prohibits human capital investment. DRR investment has the potential to ease this constraint, particularly for near-poor households, thereby allowing households to spend time on human capital investment. Through the choice-opportunity-provision effect, DRR policy selectively affects a subset of low-income households and promotes a narrowing of the human capital gap.

The externality-reinforcement effect is the extent to which DRR policy increases the pecuniary externalities between income groups regarding human capital investment. DRR policy affects the behaviors of the high-income group, unbounded by the subsistence consumption constraint, which in turn changes the human-capital-investment behavior of the low-income group through the pecuniary externalities.

4.3 Policy implications

In each of the two economies, different DRR effects dominate at different points in time, resulting in qualitatively different observations of long-term growth and distributional consequences. For example, as seen in Country M in Period 3, when the stock of DRR investment is still low and thus potential damage is not reduced enough, the negative income effect of taxation dominates. Then, in Period 5 when DRR stock is accumulated so that it works on a larger damage reduction, the positive income effect and the choice-opportunity-provision effect have a dominant impact on human capital investment. It implies that the sign of the total DRR effect can change from period to period even on a single sample path. Therefore, the possibility that the sign may change over time should be taken into account when evaluating the effect of DRR capital development on each of the economic variables. Completing the ex-post evaluation of DRR policy in Period 3 in the Country-M sample-path case for example may mislead comprehensive policy discussions.

In contrast, in the case of Country F, we observed the substitution effects dominating, with damage reduction reducing human capital investment (equivalently, larger human capital investment in Case 1). At first glance, this result sounds odd. The result depends crucially on the assumption that disasters do not cause human suffering. If the model were to incorporate a situation in which disasters cause serious illness and injury, it would describe the result that disasters slow down human capital formation by reducing both times spent working and learning. In contrast, this study assumes an ideal situation in which even low-income countries can avoid human suffering through evacuation drills and other measures. This assumption may not be supported empirically, although it does not affect the relative qualitative difference between the two countries, and moreover, it presents an important feature that human capital in the form of knowledge and skills is capital that cannot be destroyed by disasters. This is one of the essential differences between knowledge and physical production facilities.

With this in mind, the choice to devote "a larger share of available time" to learning during the period when facility damage from the disaster is significant and labor productivity does not increase, as represented by Case 1 of Country F, can be explained as a rational course of action. Labor hours can be increased after production facilities have been restored to a certain degree. However, such a choice cannot be made in Country M. The reason is that households are forced to work to obtain their minimum subsistence needs. Essentially, the period immediately after a disaster is a time when people, especially the youth who are responsible for the future development of society, should concentrate more on their studies. This numerical case study of two model countries shows that the reason why this is not possible exists in the binding nature of the subsistence consumption constraints.

Overall disaster and DRR policy effects on human capital investment and growth are complex and change over time, necessitating careful analysis using a dynamic model such as presented in this study. As seen in Country M simulation, GDP may not decrease as much due to increased labor supply, immediately following a disaster. However, negative impacts may emerge when children and youth reach working age. This is because the interruptions and withdrawals of children and youth from the learning process during disasters keep them in the low-skilled labor force. Large disasters potentially disrupt human capital investment and have an indirect impact on economic growth with a time lag. In such a case, an appropriate DRR policy could reduce a part of human-capital gaps in the long run by supporting continued post-disaster human-capital-investment opportunities for the poor.

4.4 Limitations and future research

Although this model can illustrate a wide variety of dynamic processes, the model formulation itself is necessarily rather simple. The two-period optimization framework is associated with two major issues as follows. First, the role of loans is limited; in the current model, the impact of increased borrowing comes only through the constrained demand for money in the next period. The reason is that such a short-term optimization problem cannot lead to a long-term repayment plan for households. In the future, a framework in which borrowing limits are endogenously determined by the possibility of repayment should be considered. Second, the levels of human capital and physical production capital are direct inputs of the second-period utility function. In particular, it is necessary to clarify the implications of the treatment of human capital, as it is a major concern of this study. This model implies that the motivation for human capital accumulation is not for the increase in future income but for the utility of human capital itself. This would be a drawback from the viewpoint of traditional optimization problems. On the other hand, the value of education is also pointed out, such as the value of knowledge gained to improve the quality of life, human security independently of income growth [e.g., 61], interconnectedness, and conviviality in the context of the degrowth argument [e.g., 62, 63]. From such perspectives, a framework in which human capital itself is incorporated into the utility function has some meaning.

As described above, the model in this study describes the impacts of disasters that appear with a time lag, which are interpreted as a part of indirect impacts. Such lagged impacts were figured out in Section 3 simply by comparing a sample path with disaster occurrences (e.g. the Case-1 path) with the no-disaster path (i.e., the Case-0 path). In the future, a systematic method for quantifying the lagged impacts should be developed in consideration of the possibility of various non-linear dynamic effects such as chaos. There, distributional characteristics of probabilities such as conditional expectation, variance, and value-at-risk for each future period for a variable of interest are derived through Monte Carlo simulations.

The study has other significant challenges; for example, the algorithm of finite difference methods needs improvement for numerical analysis; spatial heterogeneity also needs to be considered as a factor that may cause different exposure to disasters between wealthier and poorer households; the creation of effective demand other than DRR investment and change in money supply is also an important area for further exploration.

5 Conclusion

This study formulated a growth model of natural hazards and household heterogeneity with a special focus on human capital development. The model introduced a path of market equilibrium derived from the two-period optimization problem by each household under disaster risk and occurrences. It was designed with the intention of understanding the structure of the problem through a combination of analytical and numerical analysis. In this study, we developed the framework that handles the high-dimensional heterogeneity of households yet retains a certain level of normativity of the solution and high tractability in the analysis.

The analyses clarified that the impacts of DRR policies on human-capital-investment behavior include four effects: the income effect, the substitution effect, the choice-opportunity-provision effect, and the externality-reinforcement effect. Numerical simulations, performed for two economies modeled after Madagascar and Fiji, imply that different effects dominate in each of the two economies, resulting in qualitatively different configurations of the dynamic processes of growth and distribution.

DRR investment, when designed appropriately, had the potential to safeguard human capital investment, but such effects were not uniform across households characterized by the heterogeneous endowments. As demonstrated by Country M, DRR investment, financed via progressive taxation, most effectively safeguards post-disaster human-capital-investment opportunities. At the same time, such policy remains ineffective for those segments of the population already trapped in little or no education prior to disaster occurrence, suggesting the need for additional policy support for the most disadvantaged households. Our study also demonstrates the importance of time lags and strongly recommends policy and decision makers to design DRR policy support with due attention to a country's macroeconomic context, heterogeneities of households, and their interactions that are different even within the Global South. While our model leaves much room for improvement, we think that this framework has the potential to contribute to the discussion of policy directions by categorizing policy and aid patterns that respond to country characteristics and contexts.

Declarations

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Data Availability. The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Appendix A Interior optimum of household problem

The household problem represented by Eqs.(10a)(10b) in 2.1 contains multiple inequality constraints. Including the case splitting due to the influence of market variables, there are about 20 different case splits for obtaining the optimal solution by numerical analysis. Among them, one representative case is shown below, where the market nominal interest rate is positive, households have access to borrowing, the available budget is above the subsistence income level, and money demand and human capital investment are determined by the interior point solution.

When focusing on the interior point solution, the following substitutions of the control variables may provide a better outlook for understanding the structure of the problem.

$$\tilde{c} := c - \underline{c} > 0, \quad \tilde{a}' := a' - \underline{a} > 0, \tag{A1a}$$

$$\tilde{\eta}_z := 1 + \eta_z \ > 0, \quad \tilde{\eta}_k := 1 + \eta_k \ > 0, \tag{A1b}$$

Since the inequality constraint (10b) is not binding in this case, we can deal with the above substituted variables that are guaranteed to take positive values. Equation (5a) is transformed into the following equation:

$$\tilde{c} + Rm + P_h \eta_h + z\tilde{\eta}_z + k\tilde{\eta}_k + \tilde{a}' = y_{B0}, \tag{A2a}$$

where

$$P_h := wh_S l_D (1 - \phi_\tau), \tag{A2b}$$

$$y_{B0} := (1 + r)a + (wh_S l_D + r_K k_D + \xi)(1 - \phi_\tau) - \upsilon_\tau + z + k - \underline{c} - \underline{a}. \tag{A2c}$$

Equation (A2a) implies that R and P_h are the effective prices of money and human capital investment, respectively, which are also interpreted as opportunity costs. y_{B0} means the amount of available financial resources, net of subsistence consumption $\underline{c}$ and the lowest financial asset $\underline{a}$. Equation (A2c) implies that it is also possible to sell a physical household asset z and capital k. The interior point solutions of the optimization problem, which are attached asterisks, meet the following relations.

$$\tilde{c}^* = c^* - \underline{c} = \frac{{\gamma_c}^{\frac{1}{\theta}}}{\Gamma_{B1}} y_{B1}, \quad m^* = \frac{\left(\gamma_m R^{-1}\right)^{\frac{1}{\theta}}}{\Gamma_{B1}} y_{B1}, \tag{A3a}$$

$$h \cdot (1 + \iota \eta_h^*) = \frac{\left(\bar{\gamma}_h P_h^{-1} h\right)^{\frac{1}{\theta}}}{\Gamma_{B1}} y_{B1}, \quad z\tilde{\eta}_z^* = z \cdot (1 + \eta_z^*) = \frac{\bar{\gamma}_z^{\frac{1}{\theta}}}{\Gamma_{B1}} y_{B1}, \tag{A3b}$$

$$k\tilde{\eta}_k^* = k \cdot (1 + \eta_k^*) = \frac{\bar{\gamma}_k^{\frac{1}{\theta}}}{\Gamma_{B1}} y_{B1}, \quad \tilde{a}'^* = a'^* - \underline{a} = \frac{(\beta\gamma_a)^{\frac{1}{\theta}}}{\Gamma_{B1}} y_{B1}, \tag{A3c}$$

where

$$\bar{\gamma}_h := \iota\beta\gamma_h\bar{\gamma}_{hh}(1 - \delta_h)^{1-\theta}, \quad \bar{\gamma}_{hh} := 1 + \gamma_{hh} \cdot \left(1 - \frac{h_{S+1} - h}{h_{S+1} - h_S}\right), \tag{A3d}$$

$$\bar{\gamma}_z := \gamma_z + \beta\gamma_{zz}(1 - \delta_z)^{1-\theta}(1 - \lambda \cdot \nu_{zE} \cdot \chi_z)^{1-\theta}, \tag{A3e}$$

$$\bar{\gamma}_k := \beta\gamma_k(1 - \delta_k)^{1-\theta}(1 - \lambda \cdot \nu_{kE} \cdot \chi_k)^{1-\theta}, \tag{A3f}$$

$$\Gamma_{B1} := {\gamma_c}^{\frac{1}{\theta}} + R^{1-\frac{1}{\theta}}{\gamma_m}^{\frac{1}{\theta}} + \iota^{-1}{P_h}^{1-\frac{1}{\theta}}\bar{\gamma}_h^{\frac{1}{\theta}} h^{\frac{1}{\theta}-1} + \bar{\gamma}_z^{\frac{1}{\theta}} + \bar{\gamma}_k^{\frac{1}{\theta}} + (\beta\gamma_a)^{\frac{1}{\theta}}, \tag{A3g}$$

$$y_{B1} := y_{B0} + \iota^{-1} P_h. \tag{A3h}$$

y_{B1} means the effective disposable budget. The fraction on the right-hand-side of each of the six equations of Eqs.(A3a)-(A3c), which is a multiplier of y_{B1}, represents the effective budget share assigned to the term on the left-hand-sides. $\bar{\gamma}_z$ and $\bar{\gamma}_k$, which compose the effective budget share, include not only the weights of the utility function but the disaster arrival rate, the expected damage rates, and DRR effects. A portion of the market prices, R and w, is also included in the composition of the share. Hence a set of the effective budget shares changes every period.

The four effects of DRR on human capital investment, which were discussed in Section 4, may be explained by focusing on equations of the optimal choices introduced above. (i) The income effect is related to the change in y_{B1}. y_{B0}, which is a part of y_{B1}, includes the distribution of real GDP, which is naturally expected to increase after disaster damage is mitigated. However, a sign of the impacts on real GDP is not certain when also considering the possibility that larger reconstruction demand stimulates production. At the same time, a reduction in damage to z and k that are included in y_{B0} in Eq.(A2c) would increase household purchasing power. (ii) The substitution effect of DRR is derived from the change in the effective budget shares. A decrease in the expected damage rates increases $\bar{\gamma}_z$ and $\bar{\gamma}_k$ if θ is smaller than one (Eqs.(A3e)(A3f)), resulting in an increase in Γ_{B1} (Eq.(A3g)) and finally a negative impact on human capital investment (Eq.(A3b)). (iii) The choice-opportunity-provision effect is explained in the way that households that would have been forced to choose the corner point solution $\eta_h = 0$ are given the opportunity to choose $\eta_h > 0$ by making their available resources larger than one under the constraint through DRR. (iv) The externality-reinforcement effect is brought by changes in market variables such as w, r_K, and so on. One of the prominent cases may be the process by which DRR policies encourage investment in human capital by high-income households, resulting in a decrease in w, followed by a decrease in P_h and y_{B0} (Eqs.(A2b)(A2c)), and finally a change in human capital investment by low-income households (Eq.(A3b)).

Appendix B Values of parameters and initial states for the numerical example

Tables B1-B3 show the main exogenous variables used to set up the model economy created to emulate Madagascar for the numerical analysis in Section 3. The setup follows the following basic strategy. The base year is set at 2020. For the arrival rate of disasters, we use the percentage of years with one or more disasters between 1980 and 2020, based on [64] and [65]. The targeted disasters are floods (riverine floods) and storms (tropical cyclones). The expected damage rates of the physical capital and assets in the base year are determined by using damage data that are provided in terms of a percentage of GDP with an assumption: all damage in the year of the disaster is due to a decrease in physical production capital.

Several assumptions are introduced to compensate for the lack of data on the initial stock levels and distributions. For example, the initial total stock level of physical household assets is estimated by using the ratio of physical household assets to GDP in New Zealand, where data exist. Table B2 shows the grid of axes used to discretize the level of each state variable and the values of the marginal densities of its initial distribution. For the distribution among households of financial assets, physical household assets, and physical production capital, we assume that they are aggregated to three levels that represent lower, middle, and upper levels; which, for example, correspond to Categories 2, 3, and 5, respectively, in the case of the financial assets a. Then, we determine the values of the marginal and joint distributions so that data on the Gini coefficient of income in the base year is reproduced.

We set up the initial value of total human capital stock and its distribution in a direct and detailed manner by using the database provided by [56]. Table B3 shows the initial distribution created using the data of population, schooling years, and educational attainment for each five-year age group. We assume that human capital is

Table B1: Values of main exogenous variables for the numerical example (Country M)

Disaster					
Parameter	Value	Ide. method	Parameter	Value	Ide. method
λ	0.73171	Data	ν_{zE}, ν_{kE}	0.10590	Ass.& Cal.
ϕ_{10}	9.9074	Ass. & Cal.	ϕ_{11}	0.47178	Ass. & Cal.
χ_{z1}, χ_{k1}	1	Ass.			
Household					
Parameter	Value	Ide. method	Parameter	Value	Ide. method
θ	0.8	Ass.	β	0.9	Ass.
$\underline{c}$	9.0259	Ass.	$\underline{a}$	-15.693	Ass.
γ_c	1	Sta.	γ_m	0.65278	Cal.
γ_z	14.146	Cal.	γ_a	17.029	Cal.
γ_h	43.976	Cal.	γ_{hh}	0	Ass.
γ_{zz}	17.842	Ass.& Cal.	γ_k	35.684	Cal.
b_{Lim}	-14.386	Ass.			
Firm					
Parameter	Value	Ide. method	Parameter	Value	Ide. method
$A(1)$	0.57377	Cal.	g_A	0.02	Ass.
α_L	0.13428	Cal.	α_K	0.86572	Cal.
ρ	-0.66667	Ass.	ι	0.25322	Cal.
δ_h	0.06	Ass.	δ_z	0.03	Ass.
δ_k	0.03	Ass.	δ_D	0.03	Ass.
Initial stock					
Stock	Value	Ide. method	Stock	Value	Ide. method
$M_S(1)$	2.9221	Data	$D_R(1)$	1.5171	Data & Ass.
Total $a(1)$	2.9221	Cal.	Total $h(1)$	4.9	Data
Total $z(1)$	42.858	Data & Ass.	Total $k(1)$	46.111	Data
Price					
Price	Value	Ide. method	Price	Value	Ide. method
$W(1)$	1.8807	Cal.	$R_K(1)$	0.13756	Cal.
$P_E(1)$	1	Ass.			
κ_W	1	Ass.	κ_{RK}	1	Ass.
Policy					
Parameter	Value	Ide. method	Parameter	Value	Ide. method
μ	0.11676	Data	ϕ_τ (Case 2)	0.01	Ass.
υ_τ	- seignorage	Ass.			

- "Ide." represents Identification; "Ass.", Assumption; "Sta.", Standardization; and "Cal.", Calibration.
- The units of the following variables are defined in billion U.S. dollars: $\underline{c}$, $\underline{a}$, b_{Lim}, υ_τ, and the initial stocks except for Total $h(1)$. Total $h(1)$ is measured in years. The other variables are dimensionless quantities.

represented by a unit of the schooling years. In this numerical example, the index of educational attainment corresponds to the class of human capital, h_S, in the model. This is because it represents graduation history, which is the most easily observable indicator in many cases. The parameter value for the productivity of human investment is calibrated using the estimates of the overall average years of schooling in 2015, 2020, and 2025 as indicated by [56]. The parameter values for the production technology and

Table B2: Initial distribution of state variables (Country M)

State	Total	$\text{Categ}_{\text{State}} :=$ {Min.value : Max.value | Num. of categories, interval}	{Category Num. of non-zero density value : density value}
a	2.9221	$\text{Categ}_a := \{-13.078, 26.922 \mid 6, 8.000\}$	2:0.6, 3:0.1, 5:0.3
h	4.9	$\text{Categ}_h := \{1, 16 \mid 16, 1\}$	1:0.08052, 3:0.45077, 5:0.26188, 9:0.12951, 12:0.05588, 15:0.02144
z	42.858	$\text{Categ}_z := \{18.858, 78.858 \mid 6, 12.000\}$	2:0.6, 3:0.1, 5:0.3
k	46.111	$\text{Categ}_k := \{10.111, 118.11 \mid 10, 12.000\}$	2:0.6, 4:0.1, 8:0.3

- For example, Categ_a describes that grids that are given the category values $(1, \cdots, 6)$ on the horizontal axis in Fig.7a correspond to $(-13.078, -5.078, 2.922, 10.922, 18.992, 26.922)$ in terms of the unit of the asset.
- For example, the initial marginal distribution of a over the category $(1, \cdots, 6)$ is given by $(0, 0.6, 0.1, 0, 0.3, 0)$, where the sum of the components is unity.

Table B3: Classes and initial distribution of human capital (Country M)

Educational Attainment	No Education	Incomplete Primary	Primary
h_S	1	3	5
Initial density	0.08052	0.45077	0.26188
$\{h \mid h_S = h_S(h)\}$	1,2	3,4	5,6,7,8
Educational Attainment	**Lower Secondary**	**Upper Secondary**	**Post Secondary**
h_S	9	12	15
Initial density	0.12951	0.05588	0.02144
$\{h \mid h_S = h_S(h)\}$	9,10,11	12,13,14	15,16

utility functions listed in Table B1 are identified so that they replicate the underlying data for the National Account in the base year 2020 obtained from [55] and [66].

The values of parameters for Country F are set as listed in Tables B4 and B5. The targeted disasters are floods (coastal floods, riverine floods, flash floods) and storms (tropical cyclones). The same methods as for Country M are applied except for the following two points in addition to the base year specified in 2017. First, the value of the parameter of the expected damage rate in the initial period is determined based on an assumption that data on the expected decrease in GDP is caused by proportional decreases in labor and physical production capital. Second, because no data on the distribution of human capital exists for Fiji, we set the initial marginal distribution of human capital in the same manner as the other three stocks. It is assumed to be aggregated into four levels: “Graduated Secondary (12 years)”, “Graduated Diploma (14 years)”, “Graduated Bachelor (18 years)”, and “Graduated Master (20 years)”, while keeping in line with the Fijian education system [58]. The values are set so that the average number of years of schooling is 14.58 [57]. In addition, to replicate the Gini coefficient of income in the base year, an expansion factor is also introduced for the human capital class as noted in Table B4.

Tables B1 and B4 include a mention of the main method used to set the values of each exogenous variable. Note, however, that even in cases where a parameter value is identified through calibration, other exogenous variables used in the calculation,

Table B4: Values of main exogenous variables for the numerical example (Country F)

Disaster					
Parameter	Value	Ide. method	Parameter	Value	Ide. method
λ	0.63415	Data	ν_{zE}, ν_{kE}	0.11800	Ass.& Cal.
ϕ_{10}	8.8824	Ass. & Cal.	ϕ_{11}	0.42300	Ass. & Cal.
χ_{z1}, χ_{k1}	1	Ass.			
Household					
Parameter	Value	Ide. method	Parameter	Value	Ide. method
θ	0.8	Ass.	β	0.9	Ass.
$\underline{c}$	1.6219×10^{-6}	Ass.	$\underline{a}$	-12.244	Ass.
γ_c	1	Sta.	γ_m	0.046427	Cal.
γ_z	1.5938	Cal.	γ_a	2.2169	Cal.
γ_h	4.4651	Cal.	γ_{hh}	0	Ass.
γ_{zz}	1.9330	Ass.& Cal.	γ_k	3.8661	Cal.
b_{Lim}	-10.612	Ass.			
Firm					
Parameter	Value	Ide. method	Parameter	Value	Ide. method
$A(1)$	0.45516	Cal.	g_A	0.026	Ass.
α_L	0.27887	Cal.	α_K	0.72113	Cal.
ρ	-0.66667	Ass.	ι	0.21401	Cal.
δ_h	0.06	Ass.	δ_z	0.03	Ass.
δ_k	0.03	Ass.	δ_D	0.03	Ass.
$\{h_S \mid \text{Categ.Num.} = 1, \cdots, 10\}$		(4,7,7,14,14,14,14,28,28,35)			Ass.
Initial stock					
Stock	Value	Ide. method	Stock	Value	Ide. method
$M_S(1)$	8.1629	Data	$D_R(1)$	1.1643	Data & Ass.
Total $a(1)$	8.1629	Cal.	Total $h(1)$	14.58	Data
Total $z(1)$	38.728	Data & Ass.	Total $k(1)$	40.710	Data
Price					
Price	Value	Ide. method	Price	Value	Ide. method
$W(1)$	0.51581	Cal.	$R_K(1)$	0.13899	Cal.
$P_E(1)$	1	Ass.			
κ_W	1	Ass.	κ_{RK}	1	Ass.
Policy					
Parameter	Value	Ide. method	Parameter	Value	Ide. method
μ	0.11676	Data	ϕ_τ (Case 2)	0.01	Ass.
υ_τ	- seignorage	Ass.			

- "Ide." represents Identification; "Ass.", Assumption; "Sta.", Standardization; and "Cal.", Calibration.
- The units of the following variables are defined in billion Fijian dollars: $\underline{c}, \underline{a}, b_{\text{Lim}}$, υ_τ, and the initial stocks except for Total $h(1)$. Total $h(1)$ is measured in years. The other variables are dimensionless quantities.

such as stock values, may have been given by assumptions as described above. The influence of the assumptions indirectly extends to many parts of the setting of the exogenous variables. In this sense, compared to the settings of many other variables, we believe that we can use the results of the state-of-the-art population studies described above effectively and without significant distortion for the identification of the initial distribution of human capital in Madagascar.

Another important difference between the two country settings is the condition of subsistence consumption. Currently, the global poverty line per person per day set

Table B5: Initial distribution of state variables (Country F)

State	Total	$\text{Categ}_{\text{State}} :=$ {Min.value : Max.value | Num. of categories, interval}	{Category Num. of non-zero density value : density value}
a	8.1629	$\text{Categ}_a := \{-9.8371, 38.163 \mid 9, 6.000\}$	2:0.6, 4:0.1, 8:0.3
h	14.58	$\text{Categ}_h := \{11, 20 \mid 10, 1\}$	2:0.31, 4:0.40, 8:0.27, 10:0.02
z	38.728	$\text{Categ}_z := \{20.728, 68.728 \mid 9, 6.000\}$	2:0.6, 4:0.1, 8:0.3
k	40.710	$\text{Categ}_k := \{7.7101, 106.71 \mid 10, 11.000\}$	2:0.6, 4:0.1, 8:0.3

- The notation rules for the third and fourth columns are the same as those in Fig.B2, as illustrated by the examples below it.

by the World Bank is 2.15 USD, so in Country F, we set the level of subsistence consumption at 2.15 USD per person per day. However, if 2.15 USD per person per day were imposed on Country M, the GDP to meet that requirement for the population in 2020 would be 21.56 billion USD, which is much higher than the actual GDP of 12.25 billion USD. This would prevent most households in the model from engaging in activities other than subsistence consumption, that are, saving, building physical assets, and attending school, which would diverge from the observed facts. For this reason, we assumed the subsistence consumption level to be at 1 USD per person per day in Country M.

The crucial difference between the simulation results for the two countries depends on whether the subsistence-consumption constraint is binding or not. The numerical simulation illustrates that, despite the above difference in the subsistence-consumption levels, in Country M, post-disaster household enrollment in school is hampered by the inequality constraint of that condition. In order to meet the subsistence consumption, they are forced to work even if their productivity is low. In contrast, in Country F, the subsistence-consumption condition is not binding in the aftermath, thereby allowing households in low-income groups to continue schooling. Rather, school enrollment is encouraged as described above. Disasters have regressive effects across countries with respect to human capital formation.

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