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Macroeconomic co-benefits of DRR Investment - Assessment using the Dynamic Model of Multi-hazard Mitigation CoBenefits (DYNAMMICs) Model

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Introduction

For the global community, the coming years present an unprecedented opportunity to achieve the twin goals of sustainability and resilience. This commitment has been reaffirmed by the greater convergence seen in several recently-agreed international frameworks including *the Sendai Framework for Disaster Risk Reduction 2015-2030*, *the 2030 Agenda for Sustainable Development,* and *the New Urban Agenda - Habitat III*, all of which aim for risk-informed development, safeguarding the world's most vulnerable against the anticipated impact of climate change.

Against this backdrop, the notion of ‘co-benefits’ or ´multiple benefits´ has gained currency in the field of disaster risk reduction (DRR). Unlike the traditional view, which frames DRR investment as that primarily aimed at the protection of assets, lives, and livelihoods, the emerging discourse emphasizes the potential positive spillover effects of DRR investment. Moreover, such spill-over effects are seen to influence societal welfare, regardless of whether disasters occur, significantly shifting our locus of attention to the greater alignment of DRR investments with broader societal goals of sustainability.

As will be reviewed briefly in this background paper, the conceptualization of DRR multiple benefits has thus been largely qualitative. One of the most widely adopted framings, ‘Triple Dividends’ (Tanner et al. 2015), presents a series of narratives in which DRR investment not only protects but also fosters growth and other societal welfare. However, it falls short of providing formal theoretical underpinnings and methods for quantifying such multiple benefits.

Given that the interaction of disaster risk with DRR investment and the macroeconomy is complex, the lack of detailed understanding regarding such dynamics limits our ability to effectively design a set of DRR investment options that yield synergies between DRR and other development aspirations. Our GAR 2022 contribution is, therefore, aimed at bridging this important knowledge gap and introduces a new macroeconomic framework for quantifying the multiple benefits of DRR investment.

This complexity of the relationship between disaster risk, DRR investment and macroeconomy is hardly straightforward. Different types of DRR investment have vastly different profiles in terms of their capacity to foster the 1st, 2nd and 3rd dividends over time. Such dynamics are functions of both biophysical and economic factors, including but not limited to the prevalent levels of disaster risk prior to DRR investment, the extent of required capital (how this could potentially affect private investment) and other underlying socioeconomic drivers such as continued urbanization and therefore an increase of exposure.

This article is organized as follows: section 2 provides a brief overview of the literature on DRR multiple benefits, primarily focused on narratives behind the triple dividends of DRR. Section 3 then introduces the newly developed theoretical macroeconomic model known as **the Dynamic Model of Multi-hazard Mitigation CoBenefits (DYNAMMICs) framework,** discussing its theoretical underpinnings. Section 4 calibrates the DYNAMMICs model to the case of flood and drought risk reduction investment appraisal, using available data from Tanzania and Zambia.[1] Section 5 then discusses major policy implications of our analysis.

[1] Case countries and DRR investment options are selected as part of UNDRR project titled ‘Building Disaster Resilience to Natural Hazards in Sub-Saharan African Regions, Countries and Communities’. For more information please see: https://www.undrr.org/publication/building-disaster-resilience-natural-hazards-sub-saharan-african-regions-countries-0

DRR Multiple Benefits

Disasters triggered by natural hazards - be they floods, earthquakes, storms, droughts, or landslides - are known to affect the economy, society, and environment in a variety of ways. Following the immediate destructions of assets, lives, and livelihoods, disasters may lead to medium and long-term consequences. These include but are not limited to adverse health and educational effects (Noji 2005; Watson et al. 2007; Mochizuki et al. 2014; Cadag et al. 2017; Wang et al. 2017; Takasaki 2017), poverty and inequity (Karim and Noy 2016; Hallegatte et al. 2017) and other negative macroeconomic outcomes (Raddatz 2007; Noy 2009; Cavallo et al. 2013).

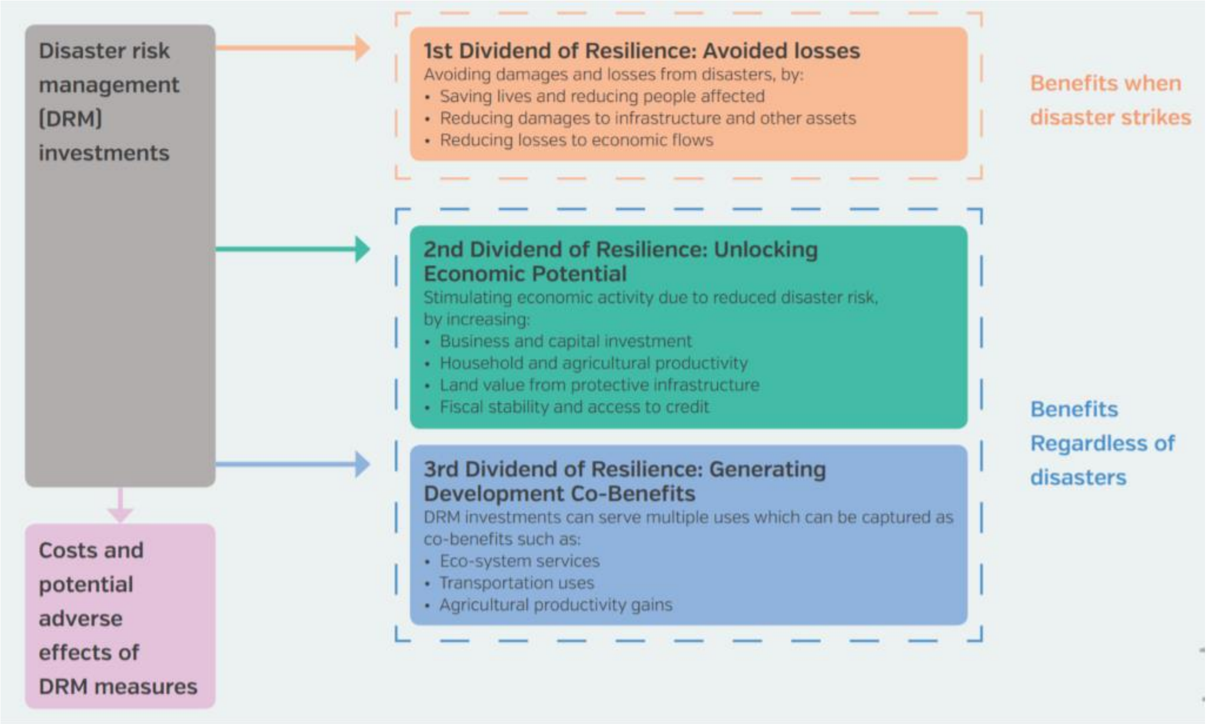
Reducing disaster risk, and building resilience against future shocks, must therefore be an integral part of our efforts to achieve sustainability. However, recent decades have seen mixed progress in this regard. Despite the considerable progress made in improving disaster preparedness such as the strengthening of national disaster management institutions and early warning systems globally, significant gaps remain in fostering proactive DRR investment.

Commonly cited reasons for under-investment in DRR include the limited visibility of DRR investment as opposed to ex-post humanitarian response and other investment priorities (Kelman 2014, UNDRR 2011). As UNDRR 2011 describes, "If DRR measures work well, they represent an invisible success; if there has been no disaster then nobody is conscious of this success, so there is no political reward (p.62)." Increased attention has thus been paid in recent years to reporting and documenting DRR successes, e.g. as seen in Cyclone Amphan of 2020 (WMO 2020).

An emerging body of literature has also provided a number of cases, conceptualizations and methods to quantify the co-benefits of DRR investment. Alves et al. (2018) for example, have proposed a framework to quantify the different categories of co-benefits related to urban 'green and blue' flood risk reduction measures such as the reduction of air pollution abatement cost, energy and Green House Gas (GHG) savings associated with green roof options and rainwater barrels. van de Ven et al. (2016) likewise provides an adaptation planning support tool with 62 blue, green and grey adaptation measures which yields multiple benefits – including urban flood reduction, drought mitigation, heat stress reduction and water quality improvement. Still others compile examples of green and blue investment options to manage hazard risks with social and environmental benefits (Foster et al. 2012, Rözer et al. 2021). However, quantification of such benefits beyond the individual investment scale, and at the macroeconomic scale in particular, remains limited.

The technical report jointly published by ODI, GFDRR and World Bank, titled "The triple dividend of resilience: Realising development goals through the multiple benefits of disaster risk management" introduced the widely adopted notion of the Triple Dividends associated with DRR investment (Figure 1).

Figure 1. The three types of dividends of DRR investments (copyright clearance pending)



Source: Tanner et al. (2015)

In their conceptualisation, DRR investments are thought to bring the following three types of benefits:

1st dividend – avoiding direct impact

DRR investment – whether it is structural (e.g. green and gray infrastructure such as retention areas, dikes and dams) or non-structural (e.g. land use planning, early warning and building codes) - reduces the immediate impacts of disasters. With DRR investment, fewer people are affected and fewer buildings, crops and other properties are destroyed when a disaster occurs. This is perhaps the most commonly perceived benefit of DRR by experts and lay persons alike. This first type of benefit is typically quantified as the difference between the expected damages before and after DRR investment.

2nd dividend – enhancing economic potential

Disaster risk is known to affect the economic decision making of individuals and firms including their savings and investment behaviors (Chantarat et al. 2015; Stephane 2016). Lacking appropriate safety nets, for example, low-income farmers may be more reluctant to adopt higher-yielding (but higher-cost) crop varieties. Likewise, firms may be less willing to invest in those geographical areas where they perceive the existence of higher disaster risk. Firms may fear that their future earnings will be adversely affected. As communities, regions and countries become safer to invest in, enhanced economic activities constitute the second dividend of DRR.

3rd dividend – generating sustainable development co-benefits

DRR investment can be designed for multi-purposes, such as a dam that provides flood mitigation, power generation, and water access or a cyclone shelter that can be used as a school and community building. DRR investment using nature-based solutions, such as a green space restores natural habitats and water cycles while providing hazard mitigation benefits such as flood, drought and landslide risk reduction. As people, communities and countries profit from these social and environmental co-benefits, these constitute the third dividend of DRR.

The above conceptualisation provides narrative examples of DRR benefits. However, such qualitative discussions fall short of providing insights as to how these factors may interact over time and yield longer-term benefits. The following sections, therefore, introduce a dynamic macroeconomic model framework termed the DYNAMMICs, that formalises the triple dividends based on macroeconomic theories. The DYNAMMICs framework will then be calibrated to the empirical cases of DRR investment (flood and drought risk management options) in Tanzania and Zambia. The simulations demonstrate how the triple dividends could be quantified, allowing for more tangible discussions of DRR benefits.

Dynamic Model of Multi-hazard Mitigation CoBenefits (DYNAMMCIs) Framework[2]

To capture the above three channels through which DRR investment leads to multiple benefits, we have selected a class of macroeconomic model, known as the Real Business Cycle (RBC) model, as the basis of the DYNAMMICs framework. While a review of economic models quantifying the impact of disasters and DRR investment is beyond the scope of the current contributing paper, Appendix 2 lists a table of common economic modeling approaches with strengths and weaknesses. The RBC model is built on the microeconomic foundations of rational representative agent behavior, capable of simulating changes in their investment, savings, consumption and other variables due to external shocks. The RBC model is typically used to simulate business cycle fluctuations due to factors such as technological shocks. The family of RBC models originates from the work of Kydland and Prescott (1977) who argued that models of economic growth need to incorporate time inconsistency of policy. Their ideas address a part of the Lucas critique stating that it is not trivial nor feasible to draw inferences from highly aggregated past observations of macroeconomic developments into the future (Tabellini, 2015). The dynamic and microeconomically founded models such as the RBC model we use in our analysis is well suited to address these shortcomings. We adopt the RBC model to simulate how disaster shocks as well as a prevalent level of disaster risk (and the effects of DRR investment) impact a country's growth trajectory. [3]

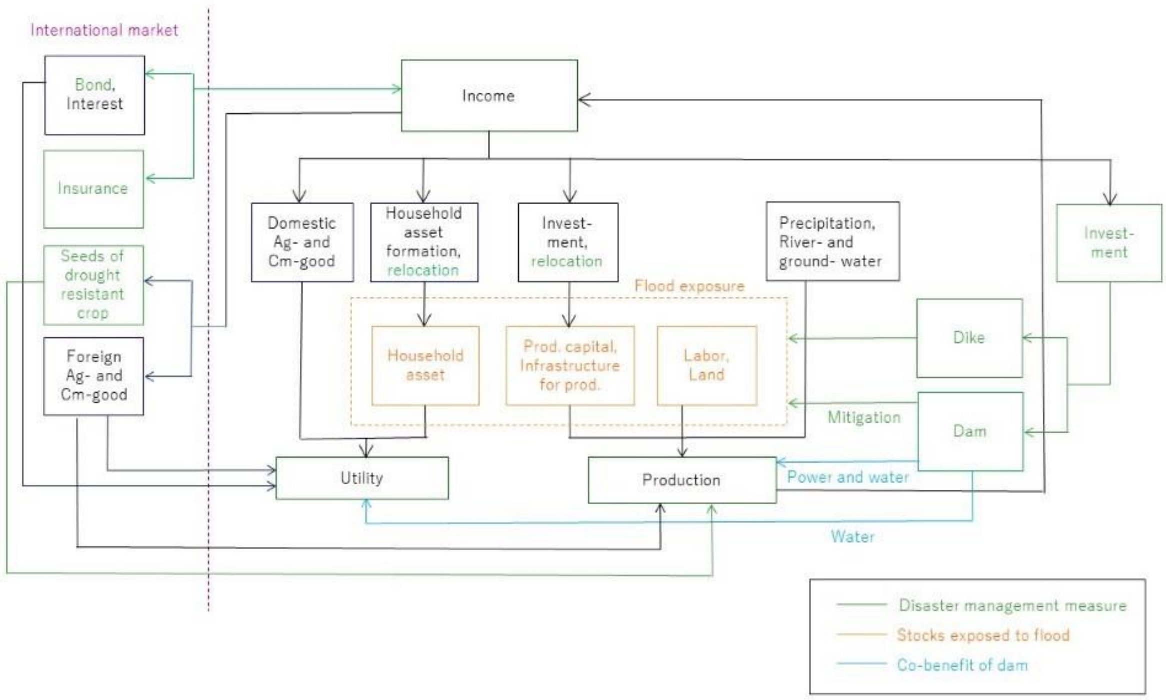
[2] A full model description is available upon request.

[3] Of course, the RBC models also have a number of limitations, in particular, issues of empirical validity remains an important areas of future study. In this contributing paper, therefore we have focused on the analysis of the differences in macroeconomic variables under various DRR investment policy options vis-à-vis the reference case.

Markets

The DYNAMMICs framework depicts an open economy divided into two spatial areas (highly exposed and less exposed areas to hazards) and two sectors (agricultural and composite good sectors). All markets are assumed to be perfectly competitive with symmetric and perfect information. Foreign bonds are traded in the international market and function as a financial vehicle for lending and borrowing and are used for financing investments in productive infrastructure and DRR. The labor market is closed, with an inelastic labor supply. Figure 2 describes the model components.

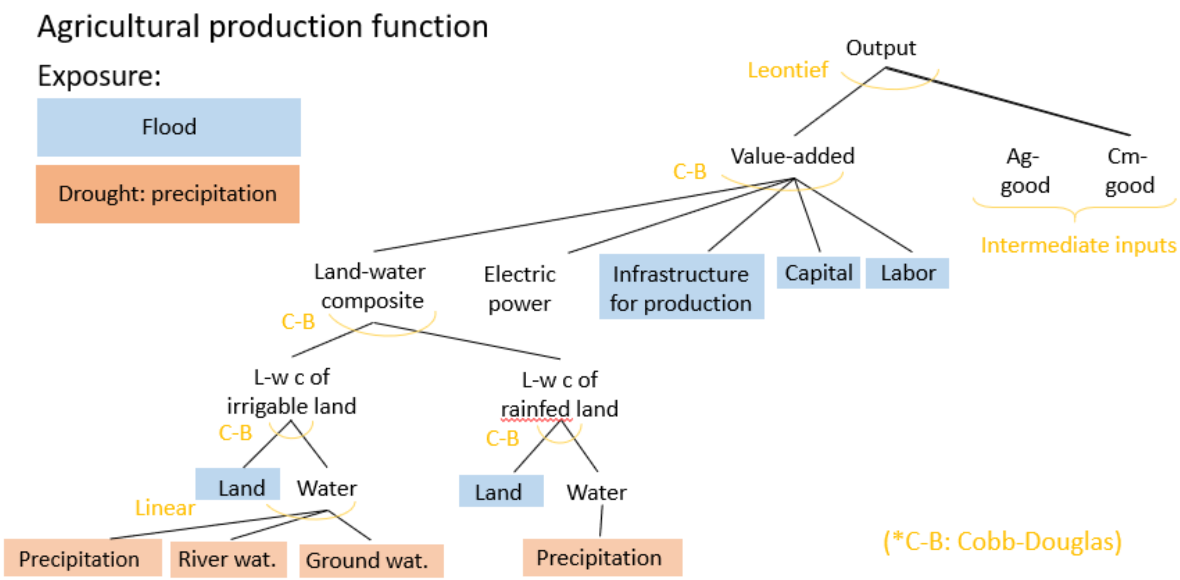
Figure 2. Schematic flow of DYNAMMICs



Technology and population growth

The economy´s domestic production activities are expressed as nested production functions shown in **Figure 3** for the agricultural sector. On the top of the nest is a familiar Leontief production function that aggregates intermediate inputs and a value-added composite. The value-added composite is composed of a land-water composite, electricity, public infrastructure, private capital and labor aggregated using a Cobb-Douglas function. The land-water composite further includes a composite of irrigated and rainfed land, also aggregated using a Cobb-Douglas function.

Figure 3. Agricultural sector nested production function



The economy is assumed to grow by both endogenous capital deepening and exogenous technical progress. We assume the Harrod-neutral technical progress which increases the efficiency of labor. In addition, we transform (i.e. detrend) the model using the effective labor unit, preventing variables from diverging. The number of households (labor supply) is assumed to grow at a constant growth rate.[4]

Hazards and DRR Investment

The DYAMMICs framework incorporates floods and droughts. The scale of individual hazard (i.e. sum of each hazard occurring in a given year) is represented by a random variable taking values between 0 (i.e. no hazard), 1 (with hazard) whose aggregate probability equals 1. For each hazard magnitude there are corresponding damage rates for each asset category, to be calibrated using probabilistic disaster risk assessment.

As shown in Figure 3, disasters are assumed to affect economic activities in a number of ways. Floods may, for example, cause the destruction of infrastructure (e.g. road, bridges and port facilities), productive capital (e.g. buildings, machinery and equipment), land and labor. Floods are also assumed to affect the country's housing stock, which is included in the representative agent's utility function. Droughts, on the other hand, affect the availability of precipitation, river and groundwater used for production activities. The availability of drinking water is also part of the representative agent's utility function. The representative agent is assumed to be risk-averse. His or her understanding of prevalent disaster risk and any changes brought about by DRR investment, therefore, leads to changes in a number of decisions including the levels of consumption, investment, savings and others.

[4] Households are assumed to have an infinite time horizon, to be identical, forward looking, and rational, with perfect perception of disaster risks and schedules of policies, and to maximize expected lifetime utility.

Quantifying Multiple Benefits of DRR

The DYNAMMICs framework conducts stochastic evaluation of an economy's alternative growth paths with and without DRR investment using the Monte Carlo simulation. The difference between the mean growth path with and without DRR investment then yields the so-called the Total Growth Effect (TGE) of DRR investment. TGE is then decomposed into the three dividends of DRR investment, namely:

- ***1st Dividend: Ex Post Damage Mitigation Effect (PDME)*** - **PDME** describes the difference between the magnitude of a disaster shock to the macroeconomy with and without DRR investment.
- ***2nd Dividend: Ex Ante Risk Reduction Effect (ARRE) -*** **ARRE** shows the benefit of DRR investment in terms of fostering other productive investments, thereby increasing GDP. **ARRE** is achieved since DRR investment safeguards further economic gains to be made from other productive investment (i.e. in economic terms, DRR investment increases the shadow value of other productive investments).[5]
- ***3rd Dividend: Co-benefit Production Expansion Effect (CPEE)***. **CPEE** describes the additional co-benefits that could be produced as a result of DRR investment, such as ecosystem services.

Figure 4. Decomposition of DRR multiple benefits

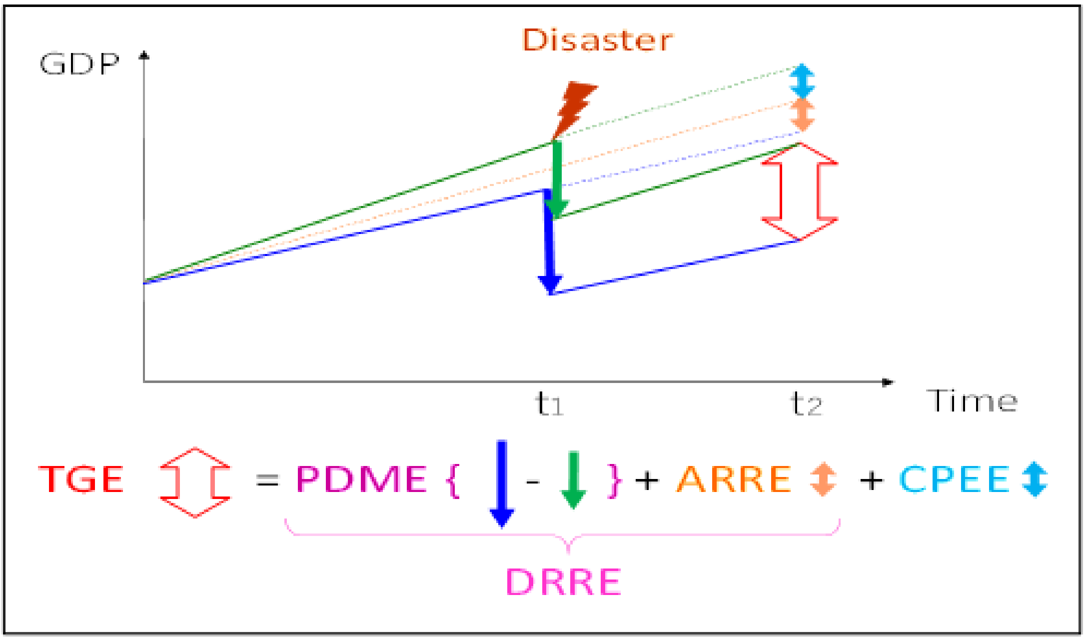


Figure 4 graphically explains the decomposition of TGE. Appendix 1 also shows detailed model equations used for TGE decomposition.

[5] It is important to note that **ARRE** is achieved whether or not disaster shocks occur in a simulated time period.

Objective Function and Solution Algorithm

The DYNAMMICs framework formulates an economy´s resource allocation decisions as a dynamic optimization problem of a representative agent. [6] The utility function of a representative agent includes an agricultural goods composite (composed of domestic and foreign agricultural goods), non-agricultural goods, residential water, and household assets.

In a typical Real Business Cycle model, the so-called No-Ponzi-Game (NPG) condition is applied to constrain debt accumulation. The NPG condition holds when the expected growth rate of debt is less than the discount rate (i.e. interest rate). Instead of the NPG condition, the DYNAMMICs framework introduces an alternative constraint on external debt so that an expected debt level at the end of a planning horizon must match that observed at the beginning (or must fall within an exogenously determined possible range of deviation).[7]

The representative agent is also assumed to be risk averse, where the degree of relative risk aversion can be chosen by a model user.[8]

[6] Unlike a typical Real Business Cycle model, the DYNAMMCIs framework optimizes across a finite time horizon that makes the planning horizon of DRR investment. For case studies in section 4, a time horizon of 30 years was used.

[7] This constraint allows for debt accumulation above the minimum threshold for those sample paths where disasters occur repeatedly, since the constraint is only applied to the expected debt level derived from the Monte Carlo Simulations. also allows for debt accumulation throughout the time horizon, as long as the terminal, expected debt level falls within a range specified.

[8] In order to avoid the so-called 'curse of dimensionality,' the DYNAMMICs framework introduces additional constraints to the solution space. Instead of deriving optimal control rules taking into account all values within the vectors of state variables, a particular rule is defined in a narrower fashion (e.g. The model defines that the rate of investment consists of three components, namely: i) baseline investment, ii) rate increment due to flood, and ii) rate increment due to drought. The solution algorithm is then applied to search for optimal rates for the three components, thereby reducing computational load compared to fully dynamic and stochastic optimization problems.

Multiple Benefits of DRR Investment in Tanzania and Zambia

Country Background

The United Republic of Tanzania (Tanzania)

Tanzania is a coastal country in East Africa, bordering Africa's three largest lakes, Lake Victoria, Lake Tanganyika and Lake Malawi. As of 2020, Tanzania had an estimated 58 million inhabitants with a near constant population growth rate of 3% since 2012. In 2017, 49.4 % of Tanzanians lived below the absolute poverty line of 1.90 US$ per day while GDP growth rates have fluctuated around 6 % over the last decade. Agriculture accounts for 28.7 % of GDP, while industry accounts for 25.1 % (World Bank 2021).

The agricultural sector employs approximately ⅔ of the country's total labor force (UNDRR, 2020c) and is especially important for those engaged in subsistence farming. The lack of safety nets, such as insurance, and the resultant adverse coping in case of disasters are among the most frequently cited factors hindering investment in agriculture. Tanzania's agricultural productivity therefore may significantly improve through risk-mitigating farming techniques and an increased uptake and quality of insurance (Janvry and Sadoulet, 2020).

Floods in Tanzania on average affect 45,000 people (0.08 % of the total population) annually. The figure is expected to grow by a factor of four or more within this century, due both to population growth and an increase in extreme events (CIMA and UNDRR 2020)[9]. Droughts also occur frequently, adversely affecting agriculture and threatening food security. The annual affected population, on average, is much larger than that of floods, at 11.8 million or 22 % of the Tanzanian population (UNDRR, 2020c).[10]

Zambia

Zambia has a land area of 752,610 sq. km and a population of 17.9 million. GDP growth has been volatile over the past decade, varying between a high of 7.6% in 2012 and a low of 1.4% in 2019. During the same period, Zambia's population grew at a rate of approximately 3% per annum. The value added by agriculture is small relative to the country's industry sector which contributed 34.9% of GDP in 2019. The lower relative share of agriculture is partly explained by the higher share of extractive industries in Zambia - the mining of copper, for example, accounts for 70% of the country's total exports. While the copper industry offers an opportunity for development through an increased cash inflow, it creates a high dependency of the Zambian economy on the volatile international copper market.

Despite its small contribution to GDP, agriculture still plays a major role: more than half (58.7%) of Zambians live below the absolute poverty line of US$1.90 per day (World Bank 2021). The share of agricultural employment in Zambia is declining but still at a high level, at 48.5 % of the country's total labor force in 2020.

In Zambia, floods and droughts have the most adverse effects on the local population and economy. Over the last two decades, floods have affected 5.2 million people while droughts have affected 4.2 million (UNDRR, 2020). Zambia is home to several large streams, especially

[9] Under RCP 8.5 or warming of up to 4°C on average. The CIMA and UNDRR (2020) analysis quantifies the magnitude of floods in terms of flood depth, horizontal flood extent, flood velocity and flood duration.
[10] Based on cumulative sum of monthly water deficits (CIMA and UNDRR, 2020).

in the Northeast area of the country, where floods are frequent and where much of the mining activities is located. While damage to bridges and other transport infrastructure may adversely affect the export of mined products, agriculture is also hampered in case of flooded fields and damage to buildings. CIMA and UNDRR (2020) project that the country's population affected by floods will increase from the current level of 20,000 (or 0.11% of the total population) on average annually to 66,000 (0.20%) under RCP 8.5 in the second half of the current century (2051-2100). Major drivers of these results are climate change, population growth and urbanization.

Droughts pose a similar threat to Zambia's economic development and food security. Currently, 7.2 million people (or 42%) on average live in areas affected by droughts. An average of 3.2 million people are estimated to be directly affected by complete or partial losses of their harvests annually. It is projected that the affected population will moderately increase to 3.7 million in the second half of this century due to climate change. This figure will increase further to 6.9 million when considering both population growth and climate change (CIMA and UNDRR 2020).

DRR Policy Options and Calibration

The model has been calibrated using macroeconomic data available from national and international sources. For both countries, the latest available input output tables were used as the base years for calibration. Flood and drought risks prior to DRR investment as well as those after DRR investment (in terms of changes in physical damage) were calibrated using CIMA/UNDRR (2019).[11] Table 1 shows the values and functional forms used to calibrate the DYNAMMICs framework.

Table 1: List of major parameters used in the macroeconomic assessments

	Values and functional forms used	References
Disaster Damage functions		
Flood damage	% of damage per damage categories and disaster levels	Calibrated based on CIMA/UNDRR (2019)
Drought damage	% of reduction in agricultural production per disaster levels	Calibrated based on CIMA/UNDRR (2019)
Flood risk reduction policy options		
Initial number of multipurpose dams	3 (Zambia) / 2* (Tanzania)	Lehner et.al. (2011)
Number of dams to be built over time horizon	2	By assumption (policy parameter)
Flood risk reduction effectiveness of dams	Exponential functions per damage categories	Calibrated based on CIMA/UNDRR (2019)
Power generation co-benefit	205 MW (operation of 365 days x 24 h at 40% efficiency)	By assumption, based on expert input

[11] Further empirical validation of our model remains an important area of this study.

Water access co-benefit	Power function per consumption categories	Calibrated based on Lehner et.al. (2011)
Construction and maintenance cost of reservoir	US$2.49M per MW	Data based on Kumakal dam in Tanzania.
Mark-up cost of insurance	5% of Annual Average Loss	By assumption
Drought risk reduction policy options		
Drought risk reduction benefit	Differences in % of reduction of agricultural production in drought years between conventional and improved varieties	Calibrated based on CIMA/UNDRR (2019)
Percentage of improved varieties adopted	50 %	By assumption (policy parameter)
Mark-up cost of insurance	5% of Annual Average Loss	By assumption

Simulation Results

The following sections describe the DYNAMMICs modeling results for structural and non-structural DRR investment options. While full accounting of the triple dividends including environmental and social co-benefits is an area of further research, this background paper examines the following options:

Structural DRR Investment

- **Construction of Reservoirs** - Primary purpose (power generation) and secondary purposes (provision of water supply and flood regulation);

Non-structural DRR Investment

- **Drought-Resistant Crops** - Primary purpose (drought risk reduction), and secondary purposes (not included in this study);
- **Exposure Management (i.e., Land Use Restriction with Planned Relocation)** - Primary purpose (flood risk reduction), and secondary purpose (not included in this study);
- **Insurances -** Primary purpose (flood and drought risk reduction) secondary purposes (not included in this study).

Structural DRR Investment - Reservoirs (i.e. hydroelectric dams with flood regulating capacity)

An ensemble modeling analysis of water discharges with and without dams was used to estimate the average flood regulating capacity of the reservoirs in Tanzania and Zambia.

Figure 5. Map of existing dams evaluated in this study.

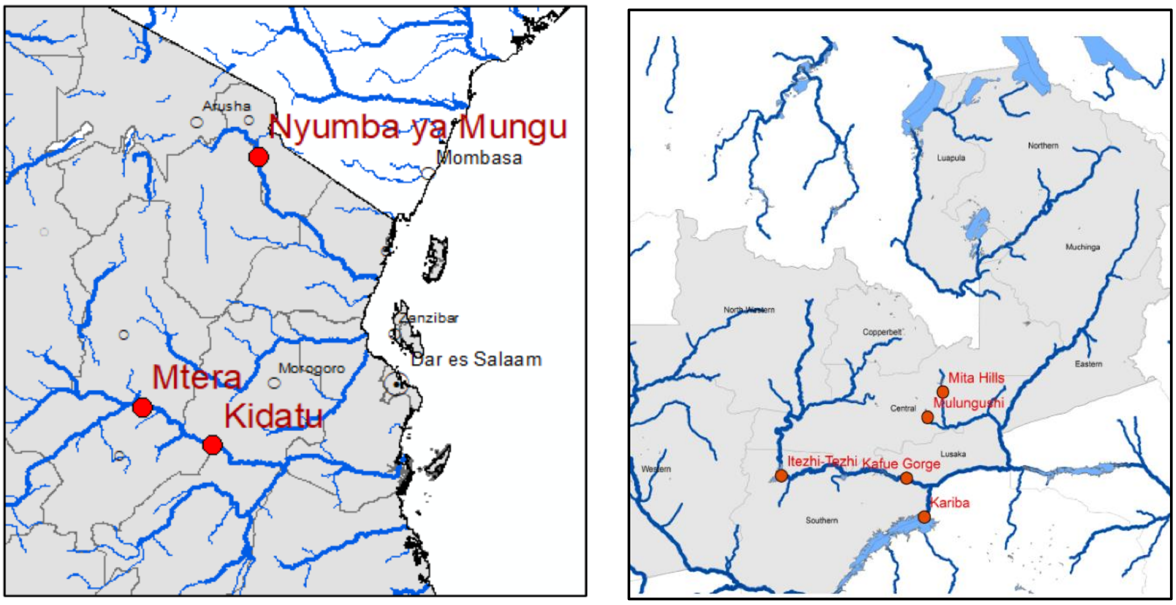
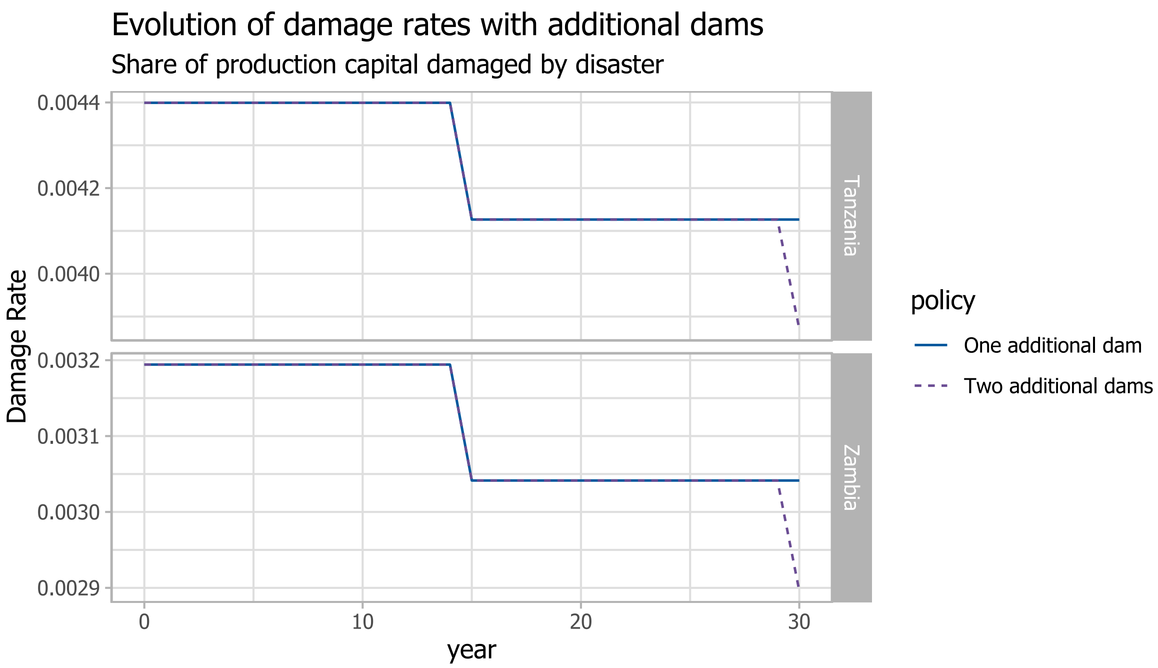


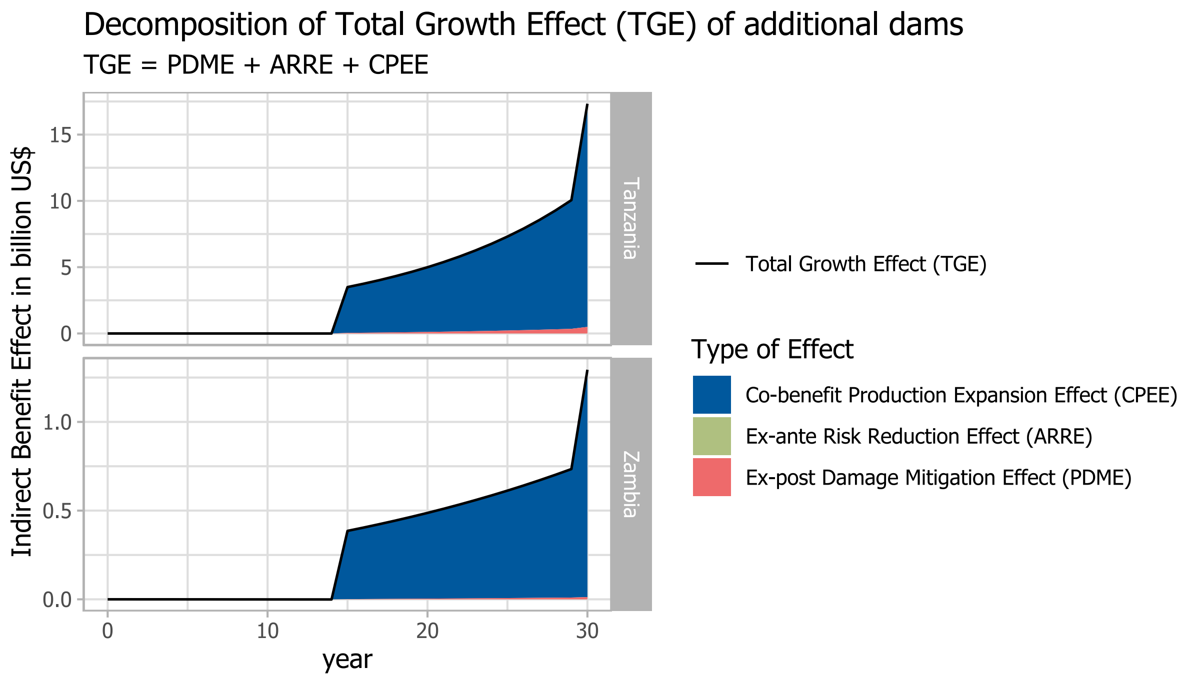
Figure 6. Changes in flood damage rate (as % of total capital stock) due to dam construction.



To estimate the effectiveness of dam construction, this study used ISI-MIP 2a data (Inter-Sectoral Impact Model Intercomparison Project – Historical validation for impact analysis) – https://www.isimip.org (Warszawski et al., 2014), comparing hydrological simulation without human intervention (Nosoc) and with human interventions including dams (Varsoc). The ensemble averages of the following four models are used: H08(Hanasaki et al., 2008, 2018); Matsiro (Pokhrel et al., 2012); DBH (Tang et al., 2007);·LPJmL (Bondeau et al., 2007; Rost et al., 2008). The estimated effectiveness was used as inputs to generate reservoir construction scenarios (Figure 6).

The DYNAMMICs framework further quantified the macroeconomic benefits of reservoir construction. This DRR policy scenario assumed that 2 hydroelectric dams have a generating capacity of 205 MW each and flood regulating capacity equivalent to the average estimated above. While the reference scenario of no additional reservoir construction resulted in a mean GDP growth of approximately 5.45% (Tanzania) and 3.39% (Zambia) over the next 30 years, the DRR policy scenario of reservoir construction resulted in a mean GDP growth of approximately 5.75% (Tanzania) and 3.59% (Zambia).

Figure 7. Decomposition of Total Growth Effect of additional dams.



A further decomposition analysis showed that, out of the estimated TGE, the 3rd dividend of CPEE (i.e. additional GDP growth stimulated by an improved supply of electricity and water), dominates, accounting for 97.2% of the growth effect at year 30. Both PDME (i.e. 1st dividend) and ARRE (i.e. 2nd dividend) remain comparatively small.

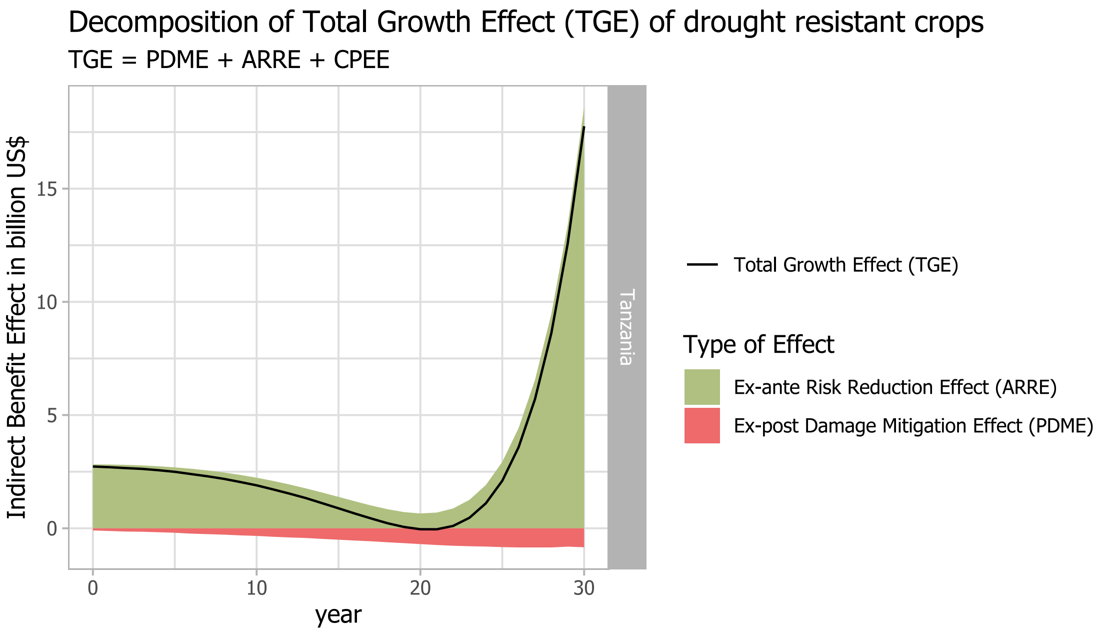
These results may be unsurprising given that the primary purpose of reservoirs is power generation. It is worth noting, however, that under the circumstance in which a large portion of domestic capital is used for public investment (such as for reservoir construction), public investment financed through a heavier tax for example dampen private investment, thereby suppressing an incentive to invest further (i.e. the potential to foster 2nd dividend). Such an effect is particularly notable when flood risk is low relative to the size of the economy and total capital stock, as is the case for Tanzania and Zambia.

Non-Structural DRR Investment

Drought Resistant Crop

The drought resistant crop scenario was evaluated for Tanzania only. This DRR policy scenario assumes that the improved short-cycle varieties of crops will be adopted for approximately 50% of agricultural sector production. The DYNAMMICs model-run indicates that the adoption of drought resistant varieties improves annual economic growth from the original level of 5.45% to 5.74%. Also, agricultural production at year 30 increases by approximately 30% relative to the baseline.

Figure 8. Decomposition of Total Growth Effect of drought resistant crops.



A further decomposition analysis shows that TGE is dominated by ARRE (or 2nd dividend) where improved water efficiency and reduced drought risk encourage agricultural producers to increase investment over time. PDME (or 1st dividend) on the other hand declines over time, mostly due to an increase in exposure and the lack of protection against the additional hazard (i.e. flood). This example illustrates the importance of balancing DRR investment across multiple hazards in order to effectively create synergies between DRR and other development objectives. As has been explained above, the inclusion of the 3rd dividend (through a detailed quantification of social and environmental benefits of drought resistant crops) remains an area for further study.

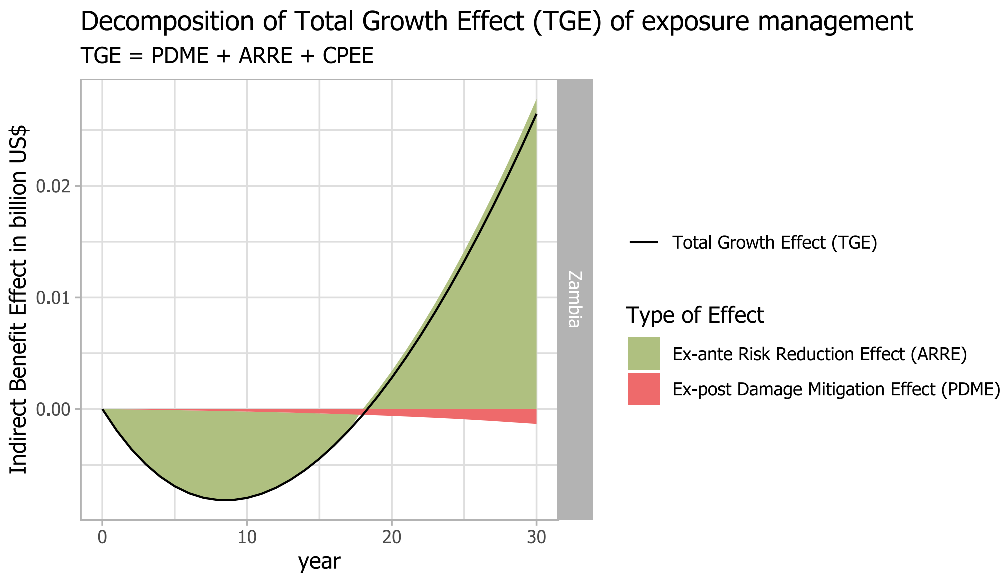
Exposure Management (i.e. Land Use Restriction with Planned Relocation)

The exposure management scenario (i.e. land use restriction with planned relocation) was evaluated for Zambia only. This DRR policy assumes that annually 8% of capital stock located in the exposed area will be relocated to the safer area in addition to the restriction of all future development in the exposed area[12]. The DYNAMMICs model-run indicates that, under this

[12] The reference scenario restricts the building of future asset in the exposed areas only.

scenario, the annual average GDP growth remained nearly constant at approximately 3.39% (with an initial decline followed by an increase which cancelled out over 30 years).

Figure 9. Decomposition of Total Growth Effect of land use restriction.



A further decomposition analysis shows that TGE is dominated by ARRE (or 2nd dividend) over time where an improved protection against floods through land use restriction fosters investment in the safe area. It is important to highlight that ARRE initially drops below zero, meaning that land use restriction reduces economic growth in the shorter run, as the restriction of land usage in the more exposed but productive land reduces the productivity of the economy as a whole. Such an effect, however, will be offset gradually by an increased safety level and hence improved productivity afforded under the new land use configuration. The modeling output also indicates a decline in PDME due to increased exposure over time. For this policy scenario, the inclusion of the 3rd dividend also remains an important area for further study.

Flood/Drought Risk Insurance

The flood/drought risk insurance scenario was evaluated for Tanzania only. This DRR policy assumes that a country purchases a multi-hazard insurance policy against drought and flood risks from the international market. The DYNAMMICs model-run indicates that the average GDP also remained nearly constant at 5.45% (with a negligible decline of 0.001%) under this scenario. This is due to the mark-up rate applied to insurance premiums (i.e. the price of insurance is set higher than the average annual expected losses of insured assets). The insurance scenario instead attains more stable GDP growth. Figure 10 shows the estimated variances of GDP growth under the two scenarios.

Figure 10. Reduction in the variance of GDP achieved under the insurance scenario.

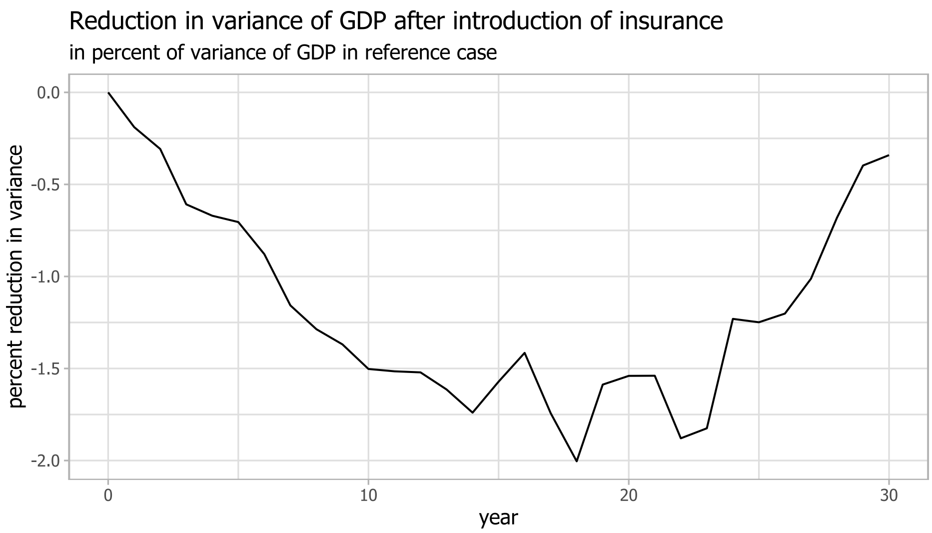
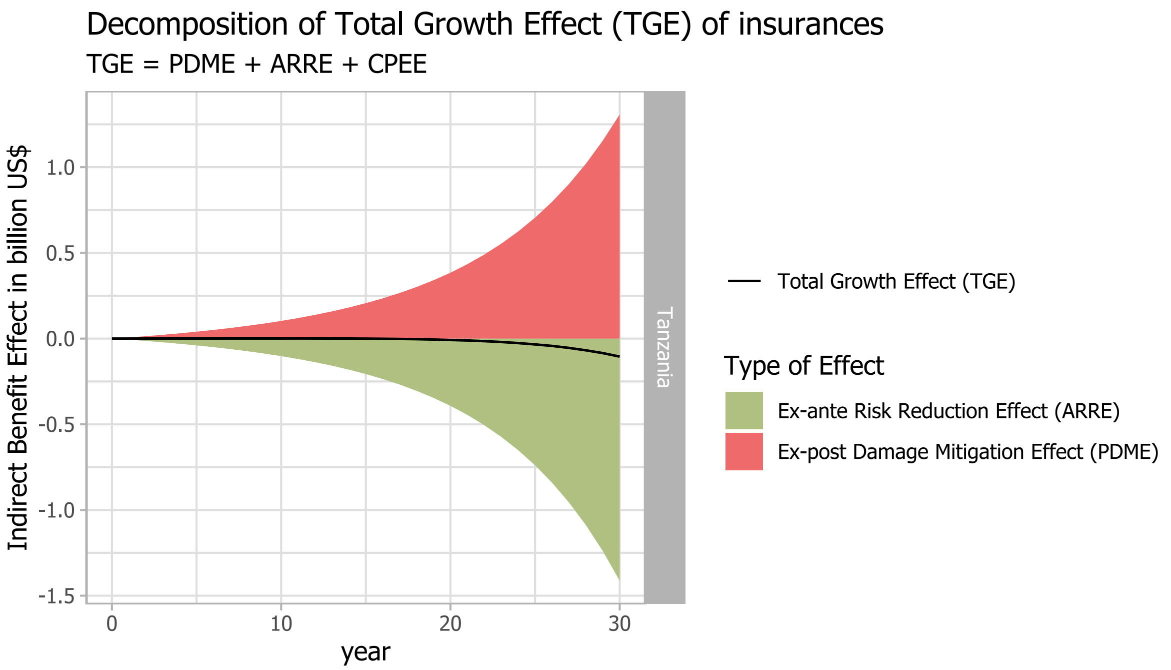


Figure 11: Decomposition of Total Growth Effect of Insurance.



A further decomposition analysis shows that TGE is dominated by PDME (or 1st dividend) where insurance payouts reduce macroeconomic losses incurred in the case of floods and droughts (Figure 11). ARRE (or 2nd dividend), on the other hand, is negative. For this policy scenario, the inclusion of the 3rd dividend also remains an area for further study.

Discussion and Conclusions

To assess the economic consequences of disaster and risk management policy, the field of macroeconomics has developed a number of theoretical and methodological approaches. These may be broadly categorized into empirically-oriented macroeconometric models and theoretically-oriented mathematical models such as the DYNAMMICs model introduced in this article.[13]

The DYNAMMICs framework, belonging to the latter category, is built on the macroeconomic theory of real business cycles, and calibrated empirically using available macroeconomic and biophysical model outputs. Such a modeling approach is more suitable for the ex-ante analysis of disaster risk and DRR policy, as it allows for the theoretically consistent evaluations of policy options, while representing pertinent economic interactions between agents and markets in a greater detail.[14] The body of literature regarding the dynamic macroeconomic models of risk has focused on various aspects including but not limited to: financial market behaviors (e.g., Barro, 2006, 2009; Gourio, 2008; Rietz, 1988; Wachter, 2013), real asset and production (e.g., Keen and Pakko, 2007; Posch and Trimborn, 2011; Segi et al., 2012 using the Dynamic Stochastic General Equilibrium (DSGE) models and Hallegatte and Ghil, 2008; Hallegatte et al., 2007 using the endogenous business cycle models). The most recent literature examines macroeconomic impacts of disasters in hazard-prone countries (Cantelmo et al., 2019; Yokomatsu et al., 2020) and in small developing states (Marto et al., 2019). Ishiwata and Yokomatsu (2018) for the first time proposed an accounting framework to decompose ex-post and ex-ante DRR policy effects.

Our approach develops this decomposition approach further and quantifies the triple dividends, namely the 1st dividend (PDME), 2nd dividend (ARRE) and 3rd dividend (CPPE). Unlike the narrative-based approach used in the previous studies, the DYNAMMICs framework has demonstrated the complexity associated with the triple dividends concept. Different DRR investment options yielded a wide ranging trajectories of the 1st, 2nd and 3rd dividends, suggesting that a more careful analysis is needed to capture the full potential of DRR investment to foster the triple dividends.

The DRR investment option using reservoirs showed that while this option had high co-benefits in terms of electricity sales and improved water access, a large public investment financed via a heavy tax hamper the potential for the 2nd dividend. This DRR investment

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[13] Empirically-oriented macro-econometric models are typically used for the ex-post assessment of policies and disaster shocks. As demonstrated by studies such as Cavallo and Noy (2009), Klomp and Valckx (2014), and Lazzaroni and van Bergeijk (2014), these models use various statistical techniques to uncover both short- and long- run impact of disasters. The major advantage of these models are the relative ease with which they can be built and implemented, yet these models can be data intensive, and being dependent on past data, are not generally suited for modelling future scenarios. Evaluating alternative policy impacts such as the multiple benefits of DRR investment will also be a challenge using this approach given the present dearth of data. At the same time, an empirical evaluation of DRR investment and its impact on variables such as saving, investment and consumption behaviors, as demonstrated in this article remains an important area of further study, for which empirical macroeconometric models may be useful.

[14] Limitations of our approach include - computational difficulties (or the so-called curse of dimensionality) and inability to evaluate short-run out of equilibrium dynamics. The latter aspect can be evaluated using methods such as agent-based modeling Poledna et.al., 2019 and demand-driven macroeconomic models (Dunz et.al., forthcoming).

option, however, may foster savings and investment on a more localised scale and the analysis of such potential is an area for further research.

The DRR investment option using drought resistant crops, illustrated the pertinence of multi-hazard risk. While the adoption of drought resistant crops incentivized the expansion of agricultural production, it remained unprotected against flood risk, thereby PDME (1st dividend) continued to decline.

The DRR investment option using land use restriction has equally shown a complex dynamic in which ARRE (2nd dividend) initially declined. This output illustrates a common challenge associated with land use restriction, in which the restriction of a highly exposed but more productive land may be seen as an obstacle to a country's economic growth. Garnering public support for this type of investment may be difficult and evaluating the policy impact over time, using a dynamic macroeconomic model such as the one presented in this study, becomes important.

Finally, the DRR investment option using insurance demonstrated that, on average, the 1st and 2nd dividends cancel out and the total growth effect was slightly negative over time. The insurance option, instead, had an important effect on reducing the variance of economic growth paths. This type of DRR option has a complementary effect on other DRR policy options (e.g. structural mitigations) where the latter options only provide protections against high frequency and low impact events.

The DYNAMMICs framework proposed in this study is capable of evaluating these multiple hazards and investment options at the same time. The model therefore is capable of evaluating the potential of DRR investment to create synergies with other development goals.

When a country, region, or community evaluates synergies and trade-offs between DRR investment and other development objectives, this article demonstrated the following policy insights:

- ***#1 Need to evaluate multi-hazard risks:*** Protection against one hazard does not guarantee protection against the other. This is particularly true in the context of developing economies where exposure may be increasing rapidly. If poorly managed, DRR investment against one hazard may in fact create more risk of another hazard. It is therefore advisable that longer-term DRR investment be evaluated in the context of multi-hazard risk, taking into account the impact of climate change.
- ***#2 Need to evaluate both short-term and longer-term costs and benefits:*** DRR investment may incur costs shorter-term, inconveniencing a particular segment of the population or being unpopular because of the perceived costs of policy adjustment. In such cases, the evaluation of DRR benefits over time, including the quantification of long-term benefits, could facilitate more productive dialogues among stakeholders.
- ***#3 Need to choose a mix of DRR options that are complementary:*** Quantification of multiple dividends help identify which DRR investment options are complementary (e.g. reservoir and insurance), while others may be substitutable (e.g. reservoir and land-use management). Each DRR investment evaluated and implemented individually may lead to an inefficient use of available resources. It is hence advisable that a country, region or community develops a longer-term multi-hazard DRR

investment strategy, where a complementary mix of DRR investment options are selected.

Appendix 1. Decomposition of DRR Benefits

The policy parameters, represented by a vector $\boldsymbol{g}$, are categorized into two groups: $\boldsymbol{g} = (\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR})$ where $\boldsymbol{g}_{MI}$ includes policy parameters for disaster mitigation, and $\boldsymbol{g}_{PR}$, those for production.

The effect of a target policy, $\boldsymbol{g}$, is measured by increase of the expected GDP from the level under the reference policy, $\boldsymbol{g}_0 = (\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR0})$; namely by Total growth effect (TGE) defined by:

$$\mathrm{TGE}(\boldsymbol{g}, t) = \mathrm{MP}(\boldsymbol{g}, t) - \mathrm{MP}(\boldsymbol{g}_0, t) \tag{1}$$

where $\mathrm{MP}(\boldsymbol{g}, t)$ represents the mean path of Monte-Carlo simulation obtained by:

$$\mathrm{MP}(\boldsymbol{g}, t) = E_\chi[\mathrm{SP}^\chi(\boldsymbol{g}, t)], \tag{2a}$$

where $\mathrm{SP}^\chi(\boldsymbol{g}, t)$ represents the GDP path of the χ-th run of the simulation.

Total growth effect (TGE) is composed of Disaster disk reduction effect (DRRE) and Co-benefit production expansion effect (CPEE), where we find two cases of decomposition that depend on the order of changing $\boldsymbol{g}_{MI}$ and $\boldsymbol{g}_{PR}$. The first case is given by:

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$$\mathrm{TGE}(\boldsymbol{g}, t) = \mathrm{MP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR}, t) - \mathrm{MP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR0}, t)$$

$$= \{\mathrm{MP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR}, t) - \mathrm{MP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR}, t)\} + \{\mathrm{MP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR}, t) - \mathrm{MP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR0}, t)\}$$

$$= \mathrm{DRRE}_1(\boldsymbol{g}, t) + \mathrm{CPEE}_1(\boldsymbol{g}, t) \tag{3a}$$

$$\text{where } \mathrm{DRRE}_1(\boldsymbol{g}, t) = \mathrm{MP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR}, t) - \mathrm{MP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR}, t) \tag{3b}$$

$$\mathrm{CPEE}_1(\boldsymbol{g}, t) = \mathrm{MP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR}, t) - \mathrm{MP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR0}, t) \tag{3c}$$

Moreover, DRRE is further decomposed into Ex-post damage mitigation effect (PDME) and Ex-ante risk reduction effect (ARRE) such like:

$$\mathrm{DRRE}_1(\boldsymbol{g}, t) = \mathrm{MP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR}, t) - \mathrm{MP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR}, t)$$

$$= \mathrm{ARRE}_1(\boldsymbol{g}, t) + \mathrm{PDME}_1(\boldsymbol{g}, t), \tag{4a}$$

$$\text{where } \mathrm{ARRE}_1(\boldsymbol{g}, t) = \mathrm{NDP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR}, t) - \mathrm{NDP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR}, t) \tag{4b}$$

$$\mathrm{PDME}_1(\boldsymbol{g}, t) = \mathrm{DRRE}_1(\boldsymbol{g}, t) - \mathrm{ARRE}_1(\boldsymbol{g}, t) \tag{4c}$$

ARRE is given by the gap of No disaster paths, represented by $\mathrm{NDP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR}, t)$ and $\mathrm{NDP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR}, t)$ above, which are more precisely defined by the GDP path where $(\phi_{t'}, \psi_{t'}, \varepsilon_{t'}) = (0, \psi_{\max}, 0)$ for all t. PDME is measured by the mean of actual loss reduction obtained at disaster times and impacts in recovery process.

Likewise, the second case of the decomposition results in:

$$\mathrm{TGE}(\boldsymbol{g}, t) = \mathrm{MP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR}, t) - \mathrm{MP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR0}, t)$$

$$= \{\mathrm{MP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR}, t) - \mathrm{MP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR0}, t)\} + \{\mathrm{MP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR0}, t) - \mathrm{MP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR0}, t)\}$$

$$= \mathrm{DRRE}_2(\boldsymbol{g}, t) + \mathrm{CPEE}_2(\boldsymbol{g}, t), \tag{5a}$$

$$\text{where } \mathrm{DRRE}_2(\boldsymbol{g}, t) = \mathrm{MP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR}, t) - \mathrm{MP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR0}, t) \tag{5b}$$

$$\mathrm{CPEE}_2(\boldsymbol{g}, t) = \mathrm{MP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR0}, t) - \mathrm{MP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR0}, t) \tag{5c}$$

Moreover,

$$\mathrm{DRRE}_2(\boldsymbol{g}, t) = \mathrm{MP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR0}, t) - \mathrm{MP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR0}, t)$$

$$= \mathrm{ARRE}_2(\boldsymbol{g}, t) + \mathrm{PDME}_2(\boldsymbol{g}, t), \tag{6a}$$

$$\text{where } \mathrm{ARRE}_2(\boldsymbol{g}, t) = \mathrm{NDP}(\boldsymbol{g}_{MI}, \boldsymbol{g}_{PR0}, t) - \mathrm{NDP}(\boldsymbol{g}_{MI0}, \boldsymbol{g}_{PR0}, t), \tag{6b}$$

$$\mathrm{PDME}_2(\boldsymbol{g}, t) = \mathrm{DRRE}_2(\boldsymbol{g}, t) - \mathrm{ARRE}_2(\boldsymbol{g}, t) \tag{6c}$$

Finally, because of no reason of choosing one of the two cases, the decomposed effects are identified by the means of the two cases as follows:

$$\mathrm{DRRE}(\boldsymbol{g}, t) = \frac{1}{2}\{\mathrm{DRRE}_1(\boldsymbol{g}, t) + \mathrm{DRRE}_2(\boldsymbol{g}, t)\} \tag{7a}$$

$$\mathrm{CPEE}(\boldsymbol{g}, t) = \frac{1}{2}\{\mathrm{CPEE}_1(\boldsymbol{g}, t) + \mathrm{CPEE}_2(\boldsymbol{g}, t)\} \tag{7b}$$

$$\mathrm{ARRE}(\boldsymbol{g}, t) = \frac{1}{2}\{\mathrm{ARRE}_1(\boldsymbol{g}, t) + \mathrm{ARRE}_2(\boldsymbol{g}, t)\} \tag{7c}$$

$$\mathrm{PDME}(\boldsymbol{g}, t) = \frac{1}{2}\{\mathrm{PDME}_1(\boldsymbol{g}, t) + \mathrm{PDME}_2(\boldsymbol{g}, t)\} \tag{7d}$$

Appendix 2. Common economic modeling approaches for disaster risk

Types of models	Advantages	Limitations	References
Empirically-oriented models			
Macro-econometric model	▪ Flexibility and ease of implementation. ▪ Suited for testing of theoretical assumptions, ex-post assessment of policy and disaster shocks.	▪ Series of empirical observations following disaster shocks and introduction of policies are needed (catastrophe event samples are rare). ▪ Limited in the amount of detail they can represent, impeding theoretical interpretation of choices and market transactions, resulting in limited predictive power. Provide a quantitative forecast within the same direction of past experience.	Cavallo and Noy (2009); Klomp and Valckx (2014); Lazzaroni and van Bergeijk (2014).
Theoretically-oriented models (calibrated empirically)			
Equilibrium-based models (where all markets represented in the mathematical model need to be in equilibrium)			
Non-stochastic macroeconomic models (IO/CGE/SAM)	▪ Less intensive data requirements, ease of implementation (including computational needs). ▪ Static models simulate a new equilibrium, while dynamic models simulate recovery process following a disaster.	▪ Unsuited for the analysis of transition and out-of-equilibrium dynamics such as immediate post disaster recovery trends. ▪ Because they do not deal with random arrivals of disaster, they are not capable of analyzing ex-ante (pre-disaster) resource allocation such as investments in production and disaster mitigation, and making of financial portfolio including insurance, bond, etc.	An adaptive regional input-output model (ARIO) (Hallegatte 2008); For review of additional CGE/IO models, see (Galbusera and Giannopoulos, 2018; Zhou and Chen, 2020).
Stochastic macroeconomic models (DSGE)	▪ Due to a dynamic framework, they are suited for the ex-ante analysis of disaster-risk-reduction (DRR) policies and alternative macroeconomic behaviors (i.e. preparedness) under risk. ▪ Results based on the rational expectation hypothesis are characterized as the normative solution that serves as a benchmark in policy discussion. ▪ DSGE models are also applied mainly with a purpose of macro-econometric verification based on past time-series data	▪ High computational needs. ▪ Unsuited for the analysis of transition and out-of-equilibrium dynamics such as immediate post disaster recovery trends. ▪ In cases that they are applied to predict the far future and possibility that unpredictable changes of technologies and other environment could happen in the process is pointed out, predictability of the models is questioned.	Dynamic Model of Multihazard Mitigation Co-benefits (DYNAMMICs), Others include (Cantelmo et al., 2019; Marto et al., 2018).

Non-equilibrium-based models (Focusing on individual behavior or capital flows and assuming no perfect equilibria on markets)			
Agent-based models	▪ Flexibility of model set-up (including high levels of geographical, sectoral and temporal disaggregation possibility, heterogeneity of economic agents). ▪ Suited for the ex-ante analysis of emergent/non-linear dynamics stemming from the interactions of individual economic agents (possible to model immediate recovery and longer-term recovery trends).	▪ High computational and data needs. ▪ Difficulty in interpretation of modeling output due to complex dynamics.	Austria ABM (Poledna et al., 2019)
System dynamics (stock-flow consistent models)	▪ Flexibility of model set-up and less computational needs, ▪ Suited for the ex-ante analysis of feedback and non-linear dynamics stemming from the interactions of macroeconomic (and financial) variables (possible to model immediate recovery and longer-term recovery trends).	▪ Less geographical/sectoral disaggregation is possible (relative to modeling approaches such as ABM).	Binary constrained Disaster (BinD) Model (Dunz et al., forthcoming).
Public finance and risk financing models (With a focus on public spending needs and limited incorporation of other economic dynamics)			
Catastrophe simulation models for public finance	▪ Less intensive data requirements, ease of implementation (including computational needs). ▪ Suited for the ex-ante analysis of policy and disaster shock. ▪ Possibility to identify single best ex-ante financing instrument	▪ Limited incorporation of macroeconomic dynamics.	Catastrophe Simulation (CATSIM) (Mechler et al., 2006, Hochrainer, 2006)(Mahul and Gurenko, 2006)

Source: adopted from IIASA (2021)

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