Creative Destruction vs Destructive Destruction : A Schumpeterian Approach for Adaptation and Mitigation

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Abstract

This article aims to demonstrate how a market exposed to a catastrophic event strives to find a balance between adaptation and mitigation policies through R&D strategies. Our analysis reveals that, within our framework, there exists no trade-off between adaptation and mitigation. Rather, the critical relationship exists between adaptation and pollution because adaptation (wealth accumulation) increases the growth rate of the economy, leading to a higher flow pollution due to the scale effect. We also investigate the long-run effects of pollution taxes on growth rates and the influence of the probability of catastrophic events on these outcomes. Our findings suggest that even with a higher likelihood of catastrophe, the economy can elevate its R&D endeavors, provided that the penalty rate stemming from an abrupt event remains sufficiently high and the economy confronts a risk of a doomsday scenario. Additionally, we illustrate that pollution taxes can foster heightened long-term growth, with the positive effects being more pronounced when the probability of catastrophe is elevated, assuming an adequately substantial penalty rate. Finally, we find that pollution growth can be higher with less polluting inputs due to a scale effect, a phenomenon akin to the Jevons-type paradox.

Keywords: Schumpeterian growth, adaptation, mitigation, uncertainty

JEL Classification: 013, O33, Q54, Q55

1 Introduction

In this paper, we take a step further to answer the following questions : How does the probability of a catastrophic event influence the process of creative destruction within the economy? What impact does a pollution[1] tax have on the growth rate, and how do the implications of catastrophe probability intersect

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[1] In the remainder of the text, we use pollution and flow pollution interchangeably. Our specification of pollution abstracts from the stock pollution. We further develop this point in the text.

with this effect? Furthermore, how does the market recalibrate the equilibrium level between adaptation and mitigation when confronted with an elevated probability of catastrophe?

Many recent reports (see EU-Innovation (2015) Road map for Climate Services [2])highlight the importance of constructing a market economy through R&D innovations that address adaptation and mitigation services, aiming to establish a low-carbon and climate-resilient economy. The climate services market aims to provide climate knowledge to society through informational means. tools.[3] These services encompass a highly detailed analysis of the prevailing environmental knowledge and R&D activities, which inform society about the ramifications of extreme climate events. In essence, climate services aim to bridge innovation with entrepreneurship, fostering the emergence of new business opportunities and market growth by increasing the resilience of an economy through targeted research and innovation investments. Additionally, they explore the means of fueling the growth of the market economy (see EU-Innovation (2015))

Indeed, it is intriguing to observe the terms "service" and "market" being associated with adaptation and mitigation activities in the report "Roadmap for Climate Services" published in 2015. This is noteworthy as the prevailing literature has predominantly examined adaptation and mitigation policies within a social optimum framework, rather than within the context of a market economy. (Zemel (2015), Bréchet et al. (2012), Tsur and Zemel (2016a)).

In recent years, dealing with catastrophic events has begun to be perceived as a business opportunity,[4] as companies can develop new services or products to adapt to catastrophic events. These offerings are anticipated to enhance competitiveness and provide market advantages that foster growth. Given this contemporary shift in adaptation and mitigation activities, a decentralized market analysis becomes crucial for rigorously assessing the long-term implications of adaptation and mitigation.

The world faces undesirable extreme events entailing significant environmental damage. Our aim in this paper is to examine how adaptation and the reduction of pollution sources (mitigation)[5] can be achieved through R&D activities managed by the market economy, even when exposed to abrupt events. As of our current knowledge, there are no studies that investigate adaptation and mitigation activities within a decentralized framework while considering the uncertain harmful events. Our contribution lies in constructing a decentralized growth model that analyzes adaptation and mitigation policies. Moreover, existing studies examine these policies using exogenous growth models, and the absence of endogenous technological progress is a notable gap. (see Zemel (2015), Bréchet et al. (2012), Tsur and Zemel (2016a), Tsur and Withagen (2012), de Zeeuw and Zemel (2012), Mavi (2020)). In a sense, our study is the first anayltical framework that focuses on adaptation and mitigation through an endogenous R&D process.

Firstly, the model in this paper builds on the literature on adaptation and mitigation (Bréchet et al. (2012)) and also incorporates the uncertain harmful events (see Tsur and Zemel (1996), Tsur and Zemel (1998)) Secondly, our model is part of the Schumpeterian growth literature, which began with the seminal paper by Aghion and Howitt (1992).

To provide the reader with insights into adaptation and mitigation analysis, first analytical studies such as Bréchet et al. (2012), Kama and Pommeret (2016), Kane and Shogren (2000) and Buob and Stephan

[2]The definition for climate services given in this report is the following : "We attribute to the term a broad meaning, which covers the transformation of climate-related data — together with other relevant information — into customized products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counselling on best practices, development and evaluation of solutions and any other service in relation to climate that may be of use for the society at large. As such, these services include data, information and knowledge that support adaptation, mitigation and disaster." (EU-Innovation (2015) - A European Research and Innovation Roadmap for Climate Services, Box1. pp 10.)

[3]An example can be a smartphone application that informs farmers about weather and how to proceed in extreme weather events.

[4]see European Commission- Road map for Climate Services 2015 and National and Sub-national Policies and Institutions.

[5]In this study, R&D aims at decreasing the pollution intensity of machines used for final good production.

(2011) explore the optimal design of adaptation and mitigation strategies. However, these studies, which concentrate on the trade-offs between adaptation and mitigation, overlook the uncertainty associated with abrupt climate events. To fill this gap in the literature, Zemel (2015) and Tsur and Zemel (2016a) introduce Poisson uncertainty into the framework of Bréchet et al. (2012) and demonstrate that a higher probability of catastrophic events leads to increased adaptation capital in the long run.

Now, we return to the Schumpeterian growth literature. The very first study that integrates environmental factors and Schumpeterian growth models is Aghion and Howitt (1997). The authors introduce pollution into a Schumpeterian growth framework and conduct a balanced growth path analysis while considering the criterion of sustainable development.[6] Grimaud (1999) extends this model to a decentralized economy in which he implements the optimum by R&D subsidies and pollution permits.

One of the earliest attempts to incorporate environmental aspects into a Schumpeterian growth model is Hart (2004). He examines the impact of a pollution tax and concludes that environmental policy can be a win-win strategy, as it increases pollution intensity while promoting long-term growth rates. Similarly, in line with this idea, Ricci (2007) demonstrates in a Schumpeterian growth model that the accumulation of knowledge drives long-term economic growth. In his model, environmental regulations compel producers of final goods to use cleaner vintages. The key distinction between Hart (2004) and Ricci (2007) is that former proposes a model in which there are only two young vintages on sale, while the latter treats a continuum of different vintages. This difference in modeling leads Ricci (2007) to conclude that stricter environmental policies do not necessarily enhance economic growth, given the diminishing marginal contribution of research and development (R&D) to growth. A recent work by Acemoglu et al. (2016) closely related to Acemoglu et al. (2012) concentrates on the competition between clean and dirty technologies. However, these models completely overlook the uncertainty surrounding abrupt climate events. A primary focus of this study is to assess how the findings of Hart (2004) and Ricci (2007) are affected by the potential occurrence of catastrophic events.

In this paper, in contrast to Hart (2004) and Ricci (2007), the benefits of R&D are twofold. Firstly, assuming that wealthier countries are more resistant to catastrophic events (see Mendhelson et al. (2006)), we demonstrate that investing in R&D increases the economy's wealth and enhances its resilience to such events. Knowledge functions as an adaptation tool primarily when abrupt events occur. In this sense, knowledge also plays a proactive role in adaptation.[7] Secondly, R&D reduces the pollution intensity of intermediate goods (i.e., mitigation), akin to Ricci (2007) , and augments total productivity, enabling a higher growth rate at the balanced growth path.

In this paper, we present two opposing effects of catastrophe probability on the creative destruction rate. The first effect is straightforward: a higher likelihood of abrupt events increases agents' impatience levels, leading to a rise in the market interest rate. Consequently, the expected value of an R&D patent decreases due to a shift in labor allocation within this sector. This phenomenon can be termed the "discount effect."

The second effect is more intriguing: with a greater likelihood of abrupt events, the marginal benefit of engaging in R&D activities grows, thanks to the resilience-enhancing properties of the knowledge stock against the impact of such events. As a result, the market interest rate decreases, and the anticipated value of R&D patents rises. This effect can be labeled the "adaptation effect."

To put it simply, as the hazard rate rises, the opportunity cost of not investing in R&D becomes more pronounced. In essence, a higher hazard rate compels the economy to allocate more resources to R&D activities. Our analysis demonstrates that when catastrophic damage surpasses a certain threshold, an increase in catastrophe probability amplifies the creative destruction rate within the economy. This outcome

[6] The sustainable development criterion necessitates that utility from consumption follows a constant or increasing trajectory in the long run.. i.e, $\frac{du(c)}{dt} \geq 0$.

[7] For a detailed discussion about proactive adaptation policy (see Zemel (2015)) .

is driven by the domination of the adaptation effect over the discount effect.

Our findings reveal that the relative level of market adaptation compared to mitigation depends on the ratio between the pollution intensity of intermediate goods and the total productivity rate of labor. Furthermore, a cleaner intermediate goods sector results in reduced adaptation to abrupt climate damages. This is based on the standard assumption that cleaner intermediate goods exhibit lower productivity. Consequently, there's a diminished growth rate and knowledge accumulation. The absence of a trade-off between adaptation and mitigation emerges from our approach to modeling adaptation. With R&D activities serving the dual roles of increasing productivity and decreasing emission intensity (mitigation), along with their supplementary role of enhancing resilience against climate-induced damage, there's no longer a clear trade-off between adaptation and mitigation. This absence arises because both adaptation and mitigation stem from the same source, namely, R&D activity. One could argue that this aligns with the recent evolution of how adaptation and mitigation are addressed within a market economy. The concept of climate service, built upon R&D activities as we further elaborate in the text, serves as one of the justifications for this perspective.[8]

In simpler terms, the economy improves both adaptation and mitigation at each point in time. Interestingly, there's another intriguing connection between adaptation and R&D activities that can develop within the economy. R&D activity reduces pollution intensity, while simultaneously aiming to augment the overall productivity of the economy. As a result, the economy's scale expands alongside increased R&D activity. If the dominance of the scale effect outweighs the decrease in emission intensity, the growth rate rises. However, in such cases, pollution growth becomes more pronounced, even when incorporating cleaner intermediate goods, due to the economy's expanded scale. This closely resembles the Jevons Paradox, which states that technological advancements enhance energy efficiency but can lead to higher pollution levels in the long run.

It is worthwhile to mention that this study does not focus on climate change, as we consider flow pollution instead of stock pollution. It is important to note that climate services aim not only to increase resilience to climate change-related shocks but also to enhance an economy's adaptation capacity against uncertain abrupt events triggered by flow pollution. We will further develop the climate services, also addressing flow pollution, through concrete examples in the remainder of this study.

Before delving into the analysis of pollution taxes, it's important to recognize that firms engage in mitigation efforts due to the imposition of a pollution tax on the utilization of polluting intermediate goods. Consequently, they invest in R&D to reduce pollution intensity and thereby alleviate the tax burden. Our model indicates a positive impact of the pollution tax on growth, akin to the findings of Ricci (2007). This is because the reduced demand for intermediate goods prompts a labor shift from the final goods sector to the R&D sector, consequently fostering economic growth. In contrast to Ricci (2007), our research demonstrates that a higher hazard rate can amplify the favorable impact of the "green" tax burden on the economy's growth rate in the long run, particularly when the penalty rate is significantly high. This effect stems from the elevated marginal benefit of R&D, which assists the economy in bolstering its resilience against catastrophic events.

The subsequent sections of the paper are structured as follows: Section 2 introduces the decentralized model, while section 3 centers on the analysis of the balanced growth path. In section 4, we investigate how the market economy manages adaptation and mitigation. Finally, section 5 concludes.

2 Model

We extend the Schumpeterian model of endogenous growth proposed by Aghion and Howitt (1997) to encompass the impact of uncertain abrupt climate events on the market economy. In doing so, our model

[8] See, e.g. Watkiss et al. (2015) for a discussion on the complementarity between adaptation and mitigation.

introduces an environmental dimension into the framework developed by Aghion and Howitt (1997) as the production process results in the emission of pollutants (as discussed in Hart (2004) and Ricci (2007)). The production process unfolds across three stages. Initially, labor is allocated to the R&D sector to enhance the productivity of intermediate goods. The pollution intensity is also a technological variable, given that successful innovations reduce the emission intensity of intermediate goods. Subsequently, the machines (intermediate goods) are supplied by a monopolistic producer of intermediate goods, who benefits from patent protection over the technology required for machine production. The production of these machines entails the emission of pollutants P, subject to a tax determined by policymakers. The final good is manufactured by combining intermediate goods and labor, with the allocation of labor influenced by the households exposed to uncertain harmful events. The probability of harmful events occurring affects the household's decisions regarding labor allocation. Hart (2004), Ricci (2007)

2.1 Production of Final Good

A homogeneous final good is produced by employing labor, L_Y , intermediate good x, according to the aggregate production function (see Stokey (1998) and Ricci (2007)).

$$Y(t) = L_Y(t)^{1-\alpha} \int_0^1 \phi(v,t)\, z(v,t)\, x(v,t)^{\alpha}\, dv, \tag{1}$$

where t serves as the continuous time index. The parameter α represents the elasticity of the intermediate good within the production function. Within the market, a continuum of diverse technologies indexed by $v \in [0,1]$ is present. The parameter $\phi(v,t)$ signifies the technology level, akin to an implicit index for labor productivity. The significant novelty within the production function, relative to Aghion and Howitt (1997) is the incorporation of heterogeneous emission intensity $z(v,t)$ for the intermediate good across different firms. This heterogeneity is defined as follows:

$$z(v,t) = \left(\frac{P(v,t)}{\phi(v,t)^{\frac{1}{\beta}}\, x(v,t)} \right)^{\alpha\beta}, \tag{2}$$

where $P(v,t)$ denotes the polluting emissions generated by a particular firm. The term $\alpha\beta$ is the share of pollution in the production function (see Appendix A). The emission intensity variable z is defined in a similar fashion to Stokey (1998) as pollution serves as an input in the production function, and its reduction leads to a decrease in production.

From equation (2), the aggregate pollution stemming from the production of intermediate goods can be formulated as:

$$P(t) = \int_0^1 P(v,t)\, dv = \int_0^1 (z(v,t))^{\frac{1}{\alpha\beta}}\, \phi(v,t)^{\frac{1}{\beta}}\, x(v,t)\, dv.$$

Contrary to Stokey (1998) and Aghion and Howitt (1997), the activity of R&D introduces a gradual alteration in pollution intensity over the long term. This variation is heterogeneous across firms within the economy (see Ricci (2007)). Unlike Stokey (1998) and Aghion and Howitt (1997), it becomes apparent that the productivity of intermediate goods does not solely depend on the labor productivity index ϕ but also on the pollution intensity z.

2.2 Final Good Producer's Program

By using the production function (1), the instantaneous profit of competitive firms is

$$\underset{x(v,t),L_Y(t)}{max} \psi(t) = Y(t) - \int_0^1 p(v,t)\, x(v,t)\, dv - w(t)\, L_Y(t), \tag{3}$$

where $p(v,t)$ and $w(t)$ denote the price of intermediate goods and the wage, respectively. The final goods sector operates under perfect competition, and the price of the final good is normalized to one. From the maximization program, we establish the demand for intermediate goods and labor by the producer of the final good

$$p(v,t) = \alpha\phi(v,t)\, z(v,t) \left(\frac{L_Y(t)}{x(v,t)}\right)^{1-\alpha}, \tag{4}$$

$$w(t) = (1-\alpha) \int_0^1 (\phi(v,t)) \left(\frac{x(v,t)}{L_Y(t)}\right)^{\alpha} dv = (1-\alpha) \frac{Y(t)}{L_Y(t)}. \tag{5}$$

When maximizing its instantaneous profit, the producer of the final good treats the technology level as a given parameter.

2.3 Intermediate Good Producer's Program

The intermediate good producer is a monopolist,[9] which provides the machines with the highest possible technology. This ensures a certain monopoly power for the intermediate good producer until a newer technology replaces its existing one (see Aghion and Howitt (1992)).

The intermediate goods producer faces a factor demand as outlined in equation (4) and supplies intermediate goods to the final goods sector. The cost of providing intermediate goods results in foregone production, which is deducted from consumption (as discussed in Nakada (2010)). In addition, the production of intermediate goods generates pollution, for which a tax $h(t)$ is imposed.

The intermediate goods sector employs designs from the R&D sector, along with resources that we refer to as "investment" or "foregone product" (see page 79, Romer (1990)). In other words, the production of intermediate goods already utilizes a portion of the final good,[10] which represents a "production loss" that might be perceived as a cost. This is how the abstraction of labor in the intermediate goods sector can be justified to avoid introducing additional costs to the analysis.

The optimization program of the intermediate goods producer is as follows:

$$\max_{x(v,t)} \pi(t) = p(v,t)\, x(v,t) - \chi x(v,t) - h(t)\, P(v,t). \tag{6}$$

Producing one unit of any machine incurs a cost of χ units of the final good (Acemoglu and Cao (2015)).[11] In the absence of a green tax, the market economy lacks incentives to reduce pollution intensity (i.e., mitigation) through R&D activities. However, as pollution is considered a cost in the intermediate goods producer's

[9] If we assume for a moment that the intermediate good sector is in perfect competition, then the price would be $p(v,t) = \chi + h(t)\,\phi(v,t)^{\frac{1}{\beta}}\, z(v,t)^{\frac{1}{\alpha\beta}}$ instead of $p(v,t) = \frac{\chi + h(t)\phi(v,t)^{\frac{1}{\beta}} z(v,t)^{\frac{1}{\alpha\beta}}}{\alpha}$. It is evident that the price is higher with a monopolistic intermediate good producer since $0 < \alpha < 1$.

[10] This is the reason why we use the term "foregone product," which already implies labor L_Y as an input. The foregone product entails a reduction in consumption, which can be observed through $c(t) = Y(t) - \chi x(t)$ (see Appendix F)

[11] This implies $Y(t) = c(t) + \chi x(t)$, which reflects the resource constraint. We will utilize this constraint to determine aggregate production further in the text.

optimization program, there is an incentive to invest in R&D[12] to mitigate this cost.

We express the supply of machines and profits of the intermediate goods producer as follows:

$$x(v,t) = \left(\frac{\alpha^2 \phi(v,t) z(v,t)}{\chi + h(t) \phi(v,t)^{\frac{1}{\beta}} z(v,t)^{\frac{1}{\alpha\beta}}} \right)^{\frac{1}{1-\alpha}} L_Y(t). \tag{7}$$

By plugging the supply function of intermediate good producer (7) in price function (4) found in final good producer's program, we can express the profit and the price of intermediate good :

$$p(v,t) = \frac{\chi + h(t) \phi(v,t)^{\frac{1}{\beta}} z(v,t)^{\frac{1}{\alpha\beta}}}{\alpha}, \tag{8}$$

and

$$\pi(v,t) = (1-\alpha) p(v,t) x(v,t). \tag{9}$$

By plugging equation (8) in (9) the profit of the intermediate good producer can be written as

$$\pi(v,t) = \frac{(1-\alpha)}{\alpha} \left(\chi + h(t) \phi(v,t)^{\frac{1}{\beta}} z(v,t)^{\frac{1}{\alpha\beta}} \right) x(v,t). \tag{10}$$

We can notice that profits are decreasing in the marginal cost of firm v : $m(v,t) = \chi + H(v,t)$ where $H(v,t) = h(t) \phi(v,t)^{\frac{1}{\beta}} z(v,t)^{\frac{1}{\alpha\beta}}$ represents the green tax burden. The green tax decreases the profits and its effect is heterogeneous across firms since final goods are differentiated in pollution intensity z i.e.

$$z(v,t) \neq z(i,t), \; for \; v \neq i, \; h(t) > 0 \implies \pi(v,t) \neq \pi(i,t). \tag{11}$$

2.4 R&D Sector

In the R&D sector, each laboratory aims to improve labor productivity and decrease the pollution intensity of intermediate goods. R&D innovations are modeled following a Poisson process with an instantaneous arrival rate λL_R, where $\lambda > 0$ can be interpreted as the creative destruction rate. Similar to Ricci (2007), we simplify the model by considering only one type of R&D firm that specializes in both productivity (ϕ) and pollution intensity (z) improvements. However, it's worth noting that this modeling choice might be considered unconventional. We justify this as follows; A two-sector R&D model would require that expected profits in both sectors should be equal in order to maintain R&D activity in both sectors.[13]

The dynamics of implicit labor productivity and pollution intensity improvements can be expressed as follows:

$$g_\phi = \frac{\dot{\bar{\phi}}_{max}(t)}{\bar{\phi}_{max}(t)} = \gamma_1 \lambda L_R, \quad \gamma_1 > 0, \tag{12}$$

$$g_Z = \frac{\dot{\underline{z}}_{min}(t)}{\underline{z}_{min}(t)} = \gamma_2 \lambda L_R, \quad \gamma_2 < 0, \tag{13}$$

where L_R represents the labor allocated to the R&D sector. A successful innovation allows the patent holder to provide the intermediate good with cutting-edge technology $\bar{\phi}$ and the lowest pollution intensity $\underline{z}$. The parameter γ_2 indicates the direction of R&D activity. The parameter γ_1 represents the magnitude of the

[12] We will delve into the effects of a pollution tax on R&D in subsequent sections.

[13] In the case of asymmetric profits, corner solutions might arise where only one type of R&D takes place. Costa (2015) proposes a two-sector R&D model that balances labor allocation between the two R&D sectors to ensure equal expected R&D values in both sectors. In his model, an increase in labor allocation to one R&D sector leads to a corresponding increase in the other sector's labor allocation, preventing corner solutions. While this approach is more realistic, it doesn't provide distinct economic insights compared to the single R&D sector model.

new innovation. A negative γ_2 indicates that innovation is environmentally friendly, with its value reflecting the extent to which innovation allows the production of cleaner intermediate goods. If we assumed $\gamma_2 = 0$, all goods would have the same pollution intensity (see Nakada (2004) for such an analysis). However, in our framework, we always have $\gamma_2 < 0$.

The free-entry condition ensures that the arbitrage condition holds;

$$w(t) = \lambda V(t), \tag{14}$$

where $V(t)$ represents the present value of expected profit streams. Equation (14) states that an agent is indifferent between working in the production sector and the R&D sector. This ensures equilibrium in the model at the balanced growth path. At equilibrium, when there is R&D activity, its marginal cost $w(t)$ is equal to its expected marginal value.

$$V(t) = \int_{\tau}^{\infty} e^{-\int_{\tau}^{t}(r(s)+\lambda L_R(s))ds} \pi\left(\bar{\phi}(t), \underline{z}(t)\right) dt, \tag{15}$$

where $\pi\left(\bar{\phi}(t), \underline{z}(t)\right)$ denotes the profit at time t of a monopoly using the leading-edge technology available $\left(\bar{\phi}(t), \underline{z}(t)\right)$. Here, r represents the interest rate, which also serves as the opportunity cost of savings, and λL_R stands for the *creative destruction rate* of the economy. The creative destruction rate reflects the extent to which incumbent firms are replaced by entrants. Essentially, it represents the survival rate of the incumbent firm, as entrants make the patents of incumbent firms obsolete. This rate can also be viewed as the depreciation rate of a patent.

Furthermore, the labor supply is fixed at unity, and the market clearing condition is given by:

$$L(t) = L_Y(t) + L_R(t) = 1. \tag{16}$$

Labor is allocated between final good production and R&D activity. The cost of R&D activity is measured as the foregone production of final goods. The cost of producing the intermediate good enters the resource constraint of the economy, which is $Y(t) = c(t) + \chi x(t)$.

2.5 Household

We present the household's maximization program, following a similar approach to Tsur and Zemel (2009). The utility function of the household is

$$\max E_T \left\{ \int_0^T u(c(t)) e^{-\rho t} dt + e^{-\rho T} \varphi(a(T)) \right\}, \tag{17}$$

where ρ represents the pure time preference of the household. $u(c(t))$ denotes the utility derived from consumption before an abrupt event occurs at an uncertain date T. $\varphi(a(t))$ represents the value function after a catastrophic event, which will be further discussed in subsequent sections. Upon integrating equation (17) by parts, the household's objective function simplifies (for detailed steps, refer to Appendix (B))

$$W_0 = \max_{c(t)} \int_0^{\infty} u\left(c(t) + \bar{\theta}\varphi(a(t))\right) e^{-\left(\rho+\bar{\theta}\right)t} dt, \tag{18}$$

where $\bar{\theta}$ represents the constant probability of a catastrophic event. The household maximizes (18) subject to

$$\dot{a}(t) = r(t) a(t) + w(t) - c(t) + R(t), \tag{19}$$

where $w(t)$ and $R(t)$ stand for wage and tax collected from the use of polluting intermediate goods, respectively. We assume that the government maintains a balanced budget for $\forall t$, i.e., $h(t) P(t) = R(t)$. The solution of the dynamic optimization program should satisfy the no-Ponzi game condition $\lim_{t\to\infty} e^{-\int_0^t r(s)ds} a(s) = 0$.

Lemma 1. $a(t) = V(t)$. *Patents for innovations ($V(t)$ is the expected value of an innovation.) are held by households.*

Proof. See Appendix C

Before deriving the Keynes-Ramsey rule from the household's maximization program, it is essential to discuss the selection of a constant hazard rate for the occurrence of harmful events.

2.5.1 Endogenous hazard rate and discussion on the use of a constant hazard rate

The use of a constant hazard rate might raise questions for some readers. To elaborate on this point, consider that the endogenous hazard rate follows the expression (as seen in Tsur and Zemel (2007))

$$\theta(P) = \bar{\theta} - \left(\bar{\theta} - \underline{\theta}\right) e^{-bP},$$

where, P represents the pollution flow resulting from the production of the final good, and $\underline{\theta}$ and $\bar{\theta}$ are the lower and upper bounds of the hazard rate, respectively. It's worth noting that $\lim_{P\to\infty} \theta(P) = \bar{\theta}$ and $\lim_{P\to 0} \theta(P) = \underline{\theta}$. In our framework, the hazard rate depends on the endogenous pollution flow P.

Flow pollution, encompassing air, water, and soil quality, is primarily determined by the release of nitrogen oxide, sulfur dioxide, and particulate matter. These emissions can adversely affect human health, cognitive abilities, building structures, and overall infrastructure quality, thereby imposing very significant harm on the economy.

In other words, abrupt events (recurrent or irreversible doomsday event) can also be triggered by the flow of pollution, not exclusively by the accumulation of pollution stock (as discussed in Bretschger and Vinogradova (2014)). Given our focus on balanced growth path analysis, employing a constant hazard rate is easily justified. To elaborate, we formally demonstrate in Appendix (N) that in our framework, an increasing hazard rate is only relevant during transition and not on the balanced growth path, which is our primary focus in this study. We can argue that during the transition, pollution exhibits both negative and positive externalities: the former arises due to an increased probability of harmful events, and the latter is associated with increased production. However, we consider only a constant probability of catastrophic events, based on the reasons mentioned earlier. Hence, we primarily consider the positive externality of pollution.

2.5.2 What happens after the catastrophic event?

We consider two different scenarios following the harmful event: recurrent harmful events and a doomsday event. For recurrent events, the post-value function takes a form similar to that in Bommier et al. (2015); Tsur and Zemel (2016b); Mavi (2020):

$$\varphi^R(a(t)) = W^B(a(t)) - \psi(a(t)), \tag{20}$$

where $\psi(a)$ represents the damage resulting from the harmful event, which is proportional to the wealth (knowledge accumulation). $W^B(a(t))$ represents the value function of the problem before the occurrence of the harmful event. The subscript R stands for recurrent events, and the subscript D stands for doomsday events, which we discuss further.

Note that $a(t)$ includes the existing stock of past innovations as well. One might argue that adaptation necessitates specific capital accumulation. We present the same framework with a specific adaptation capital to demonstrate that our main results still hold (see Appendix (M)). We will justify our modeling of adaptation below in the text.

Similar to Bréchet et al. (2012), the penalty function $\psi(.)$ is defined as follows:

A1. The penalty function $\psi(.)$**:** $\mathbb{R}+ \rightarrow \mathbb{R}+$ is twice continuously differentiable with the following properties: $\psi(a(t)) > 0$, $\psi_a(a(t)) < 0$, $\psi_{aa}(a(t)) > 0$, and $\bar{\psi} > \psi(a(t))$. This implies that the penalty function depends on the wealth stock $a(t)$ of the society.

$$\psi(a(t)) = \bar{\psi}(\omega - (1-\omega)\log(a(t))), \tag{21}$$

where $\bar{\psi}$ represents the penalty amount, and it is assumed that $0 < \omega < 1$. The parameter ω indicates the extent to which knowledge accumulation can help the economy respond to extreme events. The first term, $\bar{\psi}\omega$, represents the portion of damage that cannot be mitigated through knowledge accumulation. The second term, $-\bar{\psi}(1-\omega)\,log(a(t))$, accounts for the part of the damage that can be reduced by wealth (knowledge) accumulation thanks to R&D activity.

Discussing the concept of adaptation is important to justify the main assumptions of this study. Adaptation in this paper is not a direct policy but rather a natural consequence of accumulated wealth[14] through patent creation (i.e., $a(t) = V(t)$). Adaptation is inherent in the process of innovations through patent creation. It's important to note that the adaptation referred to here is a broader concept than specific adaptation capital. In other words, we propose that R&D not only enhances productivity and mitigates emission intensity but also plays a role in enhancing resilience against climate-induced damages. In this sense, the concept of adaptation in this study could be seen as a positive outcome of R&D activities. To provide a more comprehensive analysis, we also present an alternative framework with specific adaptation capital in Appendix (M), which yields qualitatively similar results to those presented in the main text.

Of course, adaptation does require expenditure since it involves the accumulation of stock, as extensively modeled in the existing literature (see Zemel (2015); Millner and Dietz (2011)). However, the existing literature doesn't necessarily address the relationship between adaptation and R&D measures. Separating adaptation from R&D seems somewhat unrealistic, especially considering recent efforts (see FAO (2021)) to increase the resilience of the economy. To explain further, consider the following example:

Note that crop and water quality are related to flow pollution. Sulfur dioxide and nitrogen oxide emissions cause acid rains by making the air particles acidic. This leads to water pollution and to significant decreases in soil quality, due to which abrupt harmful events are triggered. Hence, farmers face crop losses.

Climate services, enabled by R&D activities, aid farmers in adapting to crop losses due to flow pollution. Recent FAO reports[15] also emphasize that these services, driven by new technologies, involve the installation of agricultural weather stations to collect and process meteorological data, forecasting extreme events using novel methods derived from R&D.[16] These installations, distributed in a given area or region, can be viewed as numerous small R&D units, as information centers[17]apply scientific methods to analyze data and offer adaptive solutions, assisting farmers in adapting to harmful events triggered by flow pollution. This example also confirms how Climate Services help deal with flow pollution.

[14] Wealth could include assets of R&D firms in the stock market, knowledge, physical and human capital, etc.
[15] https://www.fao.org/documents/card/en/c/cb6941en
[16] Many recent methods such as machine learning, big data are used for these forecasts.
[17] Of course, analyzing this data is possible thanks to the labor L_R in R&D.

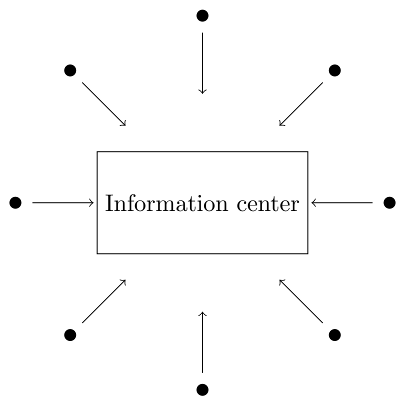


Figure 1: Climate services based on the data collection from different sources

Treating data from numerous installations could even aid in forecasting and monitoring pest and disease outbreaks. Apart from the physical costs of establishing these data centers, it's worth noting that the expenditure for this implicit adaptation, embedded in R&D methods, is already accounted for through the R&D activities, which have the opportunity cost of labor (L_R in the paper), that would otherwise be allocated to the production of final goods.

It's worth noting that the creation of patents doesn't necessarily imply that we can use these new technologies "directly" as an adaptation measure. This process implies adjustment costs to make these technologies beneficial for adapting to climate-related harmful events. However, R&D carried out by technology firms might explicitly aim to find new technologies for both adaptation and mitigation. In such cases, there might be no additional adjustment costs required to make the new technology suitable for both adaptation and mitigation. A concrete example is the "Internet of Things (IoT)," which is being used in Brazil for efficient water management (see Zukeram et al. (2023)). IoT-enabled agricultural systems optimize water usage, enhance fertilizer application, and monitor crop health. This assists farmers in adapting to changing climate conditions and also mitigates greenhouse gases. This example aligns with the concept of adaptation/mitigation through R&D (i.e., patents $a(t) = V(t)$).

Figure (1) illustrates the concept of climate services based on data collection and its utilization for adaptation and mitigation possibilities. This example could be extended to various sectors vulnerable to flow pollution, such as tourism, fishing, forestry, and more.

In order to ensure that the positive effect of wealth accumulation (the second expression in (21)) does not outweigh the unrecoverable part of the damage $\bar{\psi}\omega$, we make an assumption about the parameter ω (See Appendix D for details about Assumption 2).

A2. $\omega > \frac{(\rho+\bar{\theta}) ln(a(0))}{(\rho+\bar{\theta})(1+ln(a(0)))-g_Y}$

As Lemma 1 shows, wealth is equal to the expected value of patents (innovations). This implies that the higher an economy's innovation level (in adaptation and mitigation), the better its capacity to mitigate damage in the event of a harmful occurrence. This is because such an economy would possess a better understanding of the potential risks and impacts of a catastrophic event, and be better prepared to respond to and mitigate those impacts. Additionally, an economy with advanced climate services could potentially develop and implement more effective adaptation and mitigation strategies, such as early warning systems, disaster response plans, and infrastructure improvements (see Hotte and Jee (2022)). In essence, we argue that accumulating wealth/innovation helps an economy respond more effectively to negative consequences resulting from a catastrophic event. Empirical evidence also suggests that wealthier countries are better equipped to adapt to the consequences of harmful events and mitigate their impacts (see Mendhelson et al. (2006)). One could also argue that wealthier countries can more easily bear the costs of adaptation. However, the ability to bear this cost is also proportional to the stock of wealth a.

Now, let's consider the doomsday event. The post-value function as a function of wealth can be defined as (see Bommier et al. (2015); Tsur and Zemel (2016b); Mavi (2020) for similar definitions):

$$\varphi^D\left(a\left(t\right)\right) = u\left(c_{min}\right) - \psi\left(a\left(t\right)\right), \tag{22}$$

where $u\left(c_{min}\right) = 0$ is the utility function with consumption reduced to the subsistence level. Recall that the script D stands for the doomsday event case. Note that subsistence level consumption does not provide any utility (see Bommier et al. (2015)). In our framework, economic activity stops and consumption decreases to a subsistence level, resulting in households having no utility (i.e., $u\left(c_{min}\right) = 0$). This is a scenario similar to the COVID-19 lockdowns when economic activity had nearly halted.

It is important to note a crucial feature of our framework that justifies doing a balanced growth path analysis with the occurrence of a doomsday event. It is evident that Equation B.14 (in Appendix B) presents a stochastic problem as it implies uncertainty regarding doomsday events (or recurrent events). However, when we take the expectation of this equation, the framework simplifies into a deterministic one, effectively managing the uncertainty. We can indeed assert that the problem becomes the deterministic equivalent of the stochastic problem. This significant aspect of the model enables us to perform a balanced growth path analysis.[18]

From Lemma 1, we can observe that the household's wealth a is proportional to both the knowledge accumulation $\bar{\phi}_{max}$ and the minimum pollution intensity $\underline{z}_{min}$, which acts as a public good. Additionally, it's important to recall that mitigation efforts come at the expense of reduced adaptation, as a lower pollution intensity z leads to decreased wealth accumulation. The Lemma 1 demonstrates that wealth is directly proportional to the expected value of innovation, which can be expressed using equation (5) and the free-entry condition (14).

$$a\left(t\right) = V\left(t\right) = \frac{w\left(t\right)}{\lambda} = \frac{\left(1-\alpha\right)}{\lambda}\frac{Y\left(t\right)}{L_Y\left(t\right)} = \frac{\left(1-\alpha\right)}{\lambda}\frac{\gamma_1\alpha^{\frac{2\alpha}{1-\alpha}}}{1-\gamma_1}\left(\bar{\phi}_{max}\left(t\right)\underline{z}_{min}\left(t\right)\right)^{\frac{1}{1-\alpha}}\Omega_1\left(H\right), \tag{23}$$

where $Y\left(t\right) = \frac{\gamma_1}{1-\gamma_1}\alpha^{\frac{2\alpha}{1-\alpha}}L_Y\left(\bar{\phi}_{max}\left(t\right)\underline{z}_{min}\left(t\right)\right)^{\frac{1}{1-\alpha}}\Omega_1\left(H\right)$, represents the aggregate production function.[19] Here, $\Omega_1\left(H\right)$ is an aggregation factor that depends on the burden of the green tax H (refer to Appendix G for the details of the aggregation factor). Notably, the term $\Omega_1\left(H\right)$ arises from aggregating various firms indexed by $v \in [0,1]$.

To understand the implications of the green tax burden H, we can reformulate the profit maximization problem for the intermediate good producer v as follows: $\underset{x(v,t)}{max}\pi\left(t\right) = p\left(v,t\right)x\left(v,t\right) - \left(\chi + h\left(t\right)\left(z\left(v,t\right)\right)^{\frac{1}{\alpha\beta}}\phi\left(v,t\right)^{\frac{1}{\beta}}\right)x\left(v,t\right)$, where $h\left(t\right)\left(z\left(v,t\right)\right)^{\frac{1}{\alpha\beta}}\phi\left(v,t\right)^{\frac{1}{\beta}}$ represents the tax burden for the intermediate good producer v.

Subsequently, the (aggregate) green tax burden H;

$$H\left(t\right) = \int_0^1 H\left(v,t\right)dv = h\left(t\right)\int_0^1 \phi\left(v,t\right)^{\frac{1}{\beta}} z\left(v,t\right)^{\frac{1}{\alpha\beta}} dv. \tag{24}$$

The green tax burden $H\left(t\right)$ must be held constant in the long run to ensure the existence of a balanced growth path. To achieve this, a policy rule should be established (see Ricci (2007) and Nakada (2010)) that

[18] Normally, one can anticipate a discontinuity of the value function of the problem with the doomsday event. Indeed, this is not the case thanks to the deterministic equivalent of the stochastic problem.

[19] To make balanced growth path analysis in the context of an infinite number of firms, it is necessary to define an aggregate production function. See Appendix A for the derivation of the aggregate production function.

maintains a constant value for the green tax burden H in the long run, i.e., $\left(\frac{dH(t)}{dt} = 0\right)$.

$$g_h = -\left(\frac{g_Z}{\alpha\beta} + \frac{g_\phi}{\beta}\right). \tag{25}$$

g_i represents the growth rate of the variable i. As per the policy rule, the growth rate of the pollution tax $h(t)$ increases when emission intensity decreases and decreases when total productivity increases. This policy commitment is credible because its objective is to maintain a balanced budget. When pollution intensity decreases, tax revenues decrease due to the reduction in aggregate pollution. In contrast, when total productivity increases, both aggregate pollution and tax revenues increase. Consequently, the policymaker can decrease the growth rate of the pollution tax since tax revenues are on the rise. Unlike Ricci (2007), our policy rule also depends on productivity due to our modeling of the production function. While Ricci (2007) incorporates capital stock in their production function, composed of intermediate goods and productivity parameters, our specification describes the production function solely by the intermediate goods $x(v,t)$.

It's worth noting that, similar to Ricci (2007), we intentionally choose to exclude the influence of environmental quality/pollution on welfare and the productivity of production factors. Consequently, we can differentiate between the impact of the environmental policy (tax burden H) on growth and the positive externality of higher environmental quality, which also spurs economic growth. Otherwise, it would be challenging to distinguish whether the economic growth is driven by a positive environmental quality externality, R&D, or both.

Once the policy rule is established, it becomes possible to determine the economy's growth rate by differentiating equation (23);

$$g = g_V = g_Y = g_a = \frac{1}{1-\alpha}(g_\phi + g_Z). \tag{26}$$

The growth rate is always positive as a result of our assumption $\gamma_2 < 0 < \gamma_1$. This configuration implies that the growth rate of adaptation at the balanced growth path increases with a higher pollution intensity, γ_2. This outcome makes sense in our framework. The underlying mechanism operates as follows: An increase in pollution intensity allows for the production of more goods $Y(t)$, due to the structure of our production function. Consequently, it becomes evident that the growth rate of the value of patents $V(t)$ (and consequently, wealth) is proportionate to the growth rate of production $Y(t)$. In other words, higher production due to dirtier goods means higher wealth accumulation and hence higher adaptation due to our modeling framework.

3 Balanced Growth Path Analysis

In order to proceed with the balanced growth analysis, we begin by solving the household's problem, which involves maximizing the objective function given by equation (17), subject to the budget constraint (19). We assume a log utility function for the household's utility: $u(c(t)) = \log(c(t))$[20] to ensure analytical tractability of the model. Utilizing Lemma 1, the Keynes-Ramsey rule in the case of a doomsday event is expressed[21]

[20] It's important to note that we initiate our analysis with a CRRA utility function, specifically, $u(c(t)) = \frac{c^{1-\sigma}-1}{1-\sigma}$ and σ represents the risk aversion parameter. This utility function form is applicable when there's sudden event uncertainty. When an extreme climate event occurs, consumption reduces to a subsistence level of c_{min}. With this utility function form, it's evident that $\lim_{\sigma\to 1} \frac{c^{1-\sigma}-1}{1-\sigma} = \log(c(t))$.

[21] Furthermore, we have $g = g_c = g_Y$ at the balanced growth path (refer to equation (F1.36)).

$$g_c^D = \frac{\dot{c}(t)}{c(t)} = \left(r(t) - \left(\rho + \bar{\theta}\right) + \bar{\theta}\frac{\psi_a(a(t))}{u_c(c(t))} \right). \tag{27}$$

(see Appendix H). The growth rate of consumption at the balanced growth rate is denoted as $g = g_Y = g_c$. In the scenario of recurrent events, we have

$$g_c^R = \frac{\dot{c}(t)}{c(t)} = \left(r(t) - \rho + \bar{\theta}\frac{\psi_a(a(t))}{u_c(c(t))} \right). \tag{28}$$

The key distinction is that the discount rate term $\bar{\theta}$ cancels out in the case of recurrent events. The underlying concept is that the economy isn't entirely devastated by the catastrophic event but rather experiences recurrent inflicted damage. As outlined in equation (20), the structure of the value function following the catastrophic event remains unchanged but implies the presence of a penalty function. Naturally, this distinction significantly impacts the subsequent results presented in the paper. It's important to note that the probability of the harmful event $\bar{\theta}$ has mixed effects on labor allocation in R&D and uncertain implications for the impact of pollution tax on growth when the economy faces a probability of a doomsday event occurring. However, this isn't the case for recurrent events. In this configuration, there's always a positive impact of the "adaptation effect," as discussed below.

3.1 The Labor Allocation in Equilibrium

Once we have the Keynes-Ramsey equation, the labor allocation in the R&D sector at the balanced growth path is (see Appendix I for derivation)

$$L_R = \frac{\left(\frac{\gamma_1+\gamma_2}{1-\alpha} + \rho\right) - \varPsi_1 + \bar{\theta}\left(1 - \varPsi_2\right)}{\lambda\left(\frac{\gamma_1+\gamma_2}{1-\alpha} - 1\right) - \varPsi_1 - \bar{\theta}\varPsi_2}, \tag{29}$$

where $\varPsi_1 = \frac{\alpha\lambda\gamma_1}{(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)}$ and $\varPsi_2 = \frac{\lambda(1-\omega)\bar{\psi}}{1-\alpha}\left(1 - \frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)$. One can easily observe that the level of labor allocated in the R&D sector depends on both the catastrophic event probability, penalty rate, and the marginal cost of using a polluting intermediate good.

Proposition 1*. i) For the doomsday-event case $\varphi^D(a(t))$, assuming the log-utility $u(c) = \log(c)$, and assuming that assumptions A.1 and A.2 hold, the market allocates a higher level of labor to R&D with a higher catastrophe probability $\bar{\theta}$*

$$\text{sign}\left(\frac{\partial L_R}{\partial\bar{\theta}}\right) > 0$$

$$\text{if} \quad \bar{\psi} > \frac{\frac{\varPsi_1}{\lambda^2} + \lambda\left(1 - \frac{\gamma_1+\gamma_2}{1-\alpha}\right)}{\left(\frac{\gamma_1+\gamma_2}{1-\alpha} + \rho\right) + \lambda\left(1 - \frac{\gamma_1+\gamma_2}{1-\alpha}\right)\varPsi_2}. \tag{30}$$

ii) For the recurrent-event case, we always have sign $\left(\frac{\partial L_R}{\partial\theta}\right) > 0$.

iii) In case where there is a part of the wealth $\Delta a(t)$ destroyed due to the catastrophic event with a constant part Δ such that we have the post-value function $\varphi^D(a(t)(1-\Delta))$ with the damage function as $\psi(a(t)(1-\Delta))$, the economy has a threshold after which the damages are too important to recover;

$$\text{if} \quad \Delta > 1 - \frac{1}{\bar{\psi}}\frac{\frac{\varPsi_1}{\lambda^2} + \lambda\left(1 - \frac{\gamma_1+\gamma_2}{1-\alpha}\right)}{\left(\frac{\gamma_1+\gamma_2}{1-\alpha} + \rho\right) + \lambda\left(1 - \frac{\gamma_1+\gamma_2}{1-\alpha}\right)\varPsi_2}. \tag{31}$$

The condition becomes sign $\left(\frac{\partial L_R}{\partial \theta}\right) < 0$, *keeping the same condition for* $\bar{\psi}$ *in i).*[22]

Proof. See Appendix J

The result in i) is counter-intuitive in the sense that catastrophic uncertainty is expected to decrease R&D activity, as agents typically value the future less when there's a higher probability of a catastrophic event. Consequently, with the discount effect, the interest rate for innovation patents increases as the impatience level of agents increases. To gain a better understanding of the discount effect channel, we reformulate the interest rate for the doomsday event, which remains constant at the balanced growth path (see Appendix I for derivations).

$$r(t) = \frac{1}{1-\alpha}(g_\phi + g_Z) + \underbrace{(\rho + \bar{\theta})}_{\text{Discount effect}} - \underbrace{\frac{\bar{\theta}\bar{\psi}(1-\omega)}{\lambda(1-\alpha)}\left(1 - \frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)(1-L_R)}_{\text{Adaptation effect}}. \tag{32}$$

For the recurrent event-case, the interest rate is

$$r(t) = \frac{1}{1-\alpha}(g_\phi + g_Z) + \underbrace{\rho}_{\text{Discount effect}} - \underbrace{\frac{\bar{\theta}\bar{\psi}(1-\omega)}{\lambda(1-\alpha)}\left(1 - \frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)(1-L_R)}_{\text{Adaptation effect}}.$$

Contrary to the standard Schumpeterian growth framework, the interest rate implies an additional term we call the adaptation effect. As the economy becomes more resilient against abrupt events with wealth and knowledge accumulation, a higher abrupt event probability induces a higher marginal benefit from R&D patents. Consequently, the interest rate decreases through the adaptation effect. Finally, the expected value of R&D increases with a lower interest rate (see equation (15)). The case with recurrent events is quite straightforward since the term $\bar{\theta}$ cancels out in the discount effect term, rendering the impact of $\bar{\theta}$ unidirectional on the interest rate. In other words, the probability of a harmful event occurring, $\bar{\theta}$, always decreases the interest rate. For the rest of the analysis, we focus on the case with doomsday events.

To sum up, it follows that there exist two opposite effects of the abrupt event (doomsday) probability $\bar{\theta}$ on the interest rate, which guide investments in R&D activity. One may argue that the adaptation effect dominates the discount effect if the penalty rate $\bar{\psi}$ due to the abrupt event exceeds a certain threshold. This relies on the fact that a higher penalty rate $\bar{\psi}$ implies a higher marginal benefit of R&D.

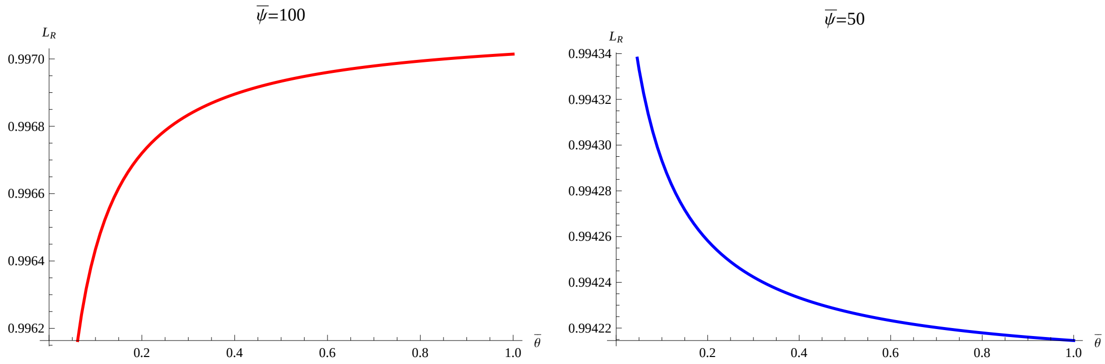
	Recurrent events	Doomsday event
L_R	$L_R^R = \frac{\left(\frac{\gamma_1+\gamma_2}{1-\alpha}+\rho\right)-\Psi_1-\bar{\theta}\Psi_2}{\lambda\left(\frac{\gamma_1+\gamma_2}{1-\alpha}-1\right)-\Psi_1-\bar{\theta}\Psi_2}$	$L_R^D = \frac{\left(\frac{\gamma_1+\gamma_2}{1-\alpha}+\rho\right)-\Psi_1+\bar{\theta}(1-\Psi_2)}{\lambda\left(\frac{\gamma_1+\gamma_2}{1-\alpha}-1\right)-\Psi_1-\bar{\theta}\Psi_2}$
g_C	$g_c^R = \left(r - \rho + \bar{\theta}\frac{\psi_a(a)}{u_c(c)}\right)$	$g_c^D = \left(r - (\rho + \bar{\theta}) + \bar{\theta}\frac{\psi_a(a)}{u_c(c)}\right)$
$\frac{\partial L_R}{\partial \bar{\theta}}$	Always positive	$\frac{\partial L_R}{\partial \bar{\theta}} > 0 \quad \bar{\psi} > \frac{\frac{\Psi_1}{\lambda^2}+\lambda\left(1-\frac{\gamma_1+\gamma_2}{1-\alpha}\right)}{\left(\frac{\gamma_1+\gamma_2}{1-\alpha}+\rho\right)+\lambda\left(1-\frac{\gamma_1+\gamma_2}{1-\alpha}\right)\Psi_2}$ $\frac{\partial L_R}{\partial \bar{\theta}} < 0 \quad \bar{\psi} < \frac{\frac{\Psi_1}{\lambda^2}+\lambda\left(1-\frac{\gamma_1+\gamma_2}{1-\alpha}\right)}{\left(\frac{\gamma_1+\gamma_2}{1-\alpha}+\rho\right)+\lambda\left(1-\frac{\gamma_1+\gamma_2}{1-\alpha}\right)\Psi_2}$
$\frac{\partial L_R}{\partial H}$	$\frac{\partial L_R^R}{\partial H} = \frac{\left(\frac{1-\lambda}{1-\alpha}(\gamma_1+\gamma_2)+\lambda\right)\left(\bar{\theta}Z_1+Z_2\right)}{(b-\alpha\Psi_2-\Psi_1)^2}$	$\frac{\partial L_R}{\partial H} = \frac{[a-b+(1-\theta)\Psi_2]Z_1+[a+(1-\theta)b-(1-\theta)\Psi_1]Z_2}{(b-\alpha\Psi_2-\Psi_1)^2} \gtrless 0$ See conditions below

Table 1: Summarizing results in the case of recurrent events and doomsday event at the equilibrium

We illustrate the Proposition 1. graphically to confirm the mechanisms presented above through a numerical exercise.[23]

[22] *I am grateful to an anonymous referee for reminding this point.*

[23] The parameter values for the graphic below are as follows; $\rho = 0.05$, $\omega = 0.8$, $\psi = 1$ and 3 , $\alpha = 0.3$, $\beta = 0.05$, $\lambda = 0.7$,



(a) $\bar{\theta}$ increasing L_R (b) $\bar{\theta}$ decreasing L_R

Figure 2: The effect of the abrupt event probability on labor allocation in R&D

How can abrupt events and adaptation create business opportunities and affect competitiveness, ultimately promoting long-run growth in a market economy? To answer this question, we need to examine the relationship between labor allocation in R&D and the probability of abrupt events. R&D activity alters the distribution of intermediate goods by shifting it towards cleaner options. Consequently, the burden of green taxes becomes more stringent as policymakers commit to an increasing trajectory of pollution taxes on cleaner intermediate goods. To comprehend this mechanism, we express the marginal cost of using intermediate goods as follows (refer to Appendix K for the derivation):

$$m(\tau) = \chi + e^{g_h \tau} H, \tag{33}$$

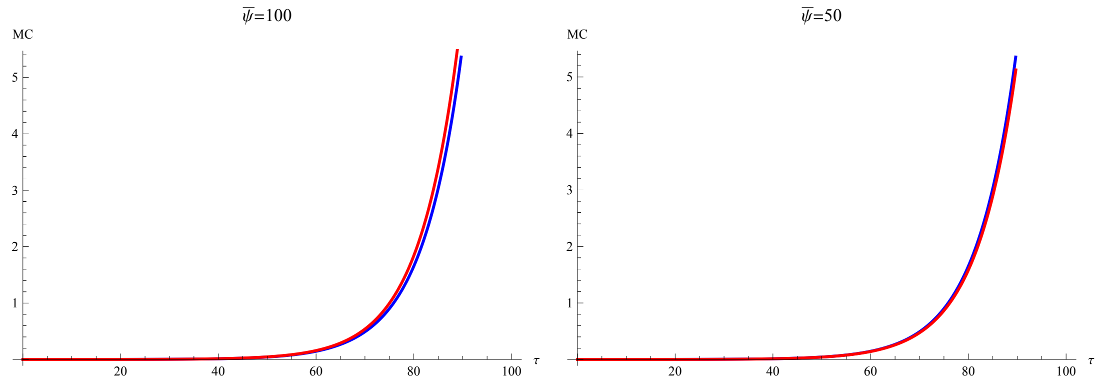
where τ represents the age of an intermediate good. It's important to note that older vintages tend to be dirtier than younger ones. Indeed, the environmental policy rule by the policymaker creates a green crowding-out effect similar to Ricci (2007).

According to Figure (3a)[24], the marginal cost of using the intermediate good increases when the abrupt event probability $\bar{\theta}$ increases the labor allocation in R&D. This is because R&D activity increases, and g_h becomes higher.[25] As a result, a higher abrupt event probability $\bar{\theta}$ displaces a greater number of old vintages, which are dirtier, from the market and replaces them with cleaner intermediate goods. It's worth noting that older vintages entail a higher green tax burden, which reduces competitiveness in the economy. Consequently, an increase in the abrupt event probability $\bar{\theta}$ enhances the competitiveness of the economy when the market shifts labor to the R&D sector.

$\gamma_2 = -0.6$, $\gamma_1 = 0.9$, $H = 0.1$, $\chi = 2$. Note that most of the parameter values except α and ρ (coming from Nordhaus (2008)) are plausible parameter values but not coming from a calibration exercise since the aim of the paper is not to propose a quantitative growth model. The numerical illustrations serve the purpose of aiding readers in quickly grasping the main results. Sometimes, below we change the parameter values to illustrate different scenarios, such as the impact of the cleanliness rate on the adaptation/mitigation ratio and so on.

[24] The parameter values for the graphic below are as follows: $\rho = 0.05$, $\omega = 0.8$, $\psi = 50$ and 100, $\alpha = 0.3$, $\beta = 0.05$, $\lambda = 0.1$, $\gamma_2 = -0.25$, $\gamma_1 = 0.75$, $H = 0.1$, $\chi = 2$.

[25] Equivalently, this implies that environmental policy becomes more stringent.



(a) $\bar{\theta}$ increasing L_R (b) $\bar{\theta}$ decreasing L_R

Figure 3: The effect of the abrupt event probability (doomsday event) on the competitiveness of different vintages

However, a higher abrupt event probability can also allow a higher number of firms to remain on the market with dirty intermediate goods. This scenario is possible only if the abrupt event probability decreases the expected value of R&D. In Figure (3b), we observe that the marginal cost of using the intermediate good decreases concerning the abrupt event probability $\bar{\theta}$ since the green tax burden becomes less stringent with a lower level of labor in the R&D sector.

Proposition 2. *(i) Let assumptions A.1 and A.2 hold, and suppose* $\frac{\bar{\gamma}+1}{b}=0$, *where* $\bar{\gamma}=\frac{1}{1-\alpha}\left(1+\frac{\gamma_2}{\gamma_1}\right)+\frac{1}{\gamma_1}-1$ *in the case of a doomsday catastrophic event* $\varphi^D(a)$, *the effect of pollution tax on growth is positive*

$$\text{sign}\left(\frac{\partial L_R^D}{\partial H}\right)>0$$

if the elasticity of aggregation factor with respect to the green tax burden H satisfies the condition 1

$$-\frac{\frac{\partial\Omega_1(H)}{\Omega_1(H)}}{\frac{\partial H}{H}}>-\frac{\frac{\partial\Omega_2(H)}{\Omega_2(H)}}{\frac{\partial H}{H}},$$

and the condition 2;

$$H+\chi<2.$$

(ii) The positive effect of pollution tax on growth increases positively with catastrophic event probability $\bar{\theta}$

$$sign\left(\frac{\partial}{\partial\bar{\theta}}\left(\frac{\partial L_R}{\partial H}\right)\right)>0.$$

if the amount of penalty satisfies the condition $\bar{\psi}>g(.)$, where the term $g(.)$ is a function of constant parameters of the model (see Appendix L for details).

(ii) With the same assumptions as in (i), in the case of recurrent harmful events $\varphi^R(a)$, the effect of the pollution tax on growth is positive

$$\text{sign}\left(\frac{\partial L_R^R}{\partial H}\right)>0.$$

if conditions 1 and 2 hold.

Proof. See Appendix L.

The economic explanation for the positive effect of pollution tax on growth is as follows: the pollution tax decreases the demand for intermediate goods since it becomes more costly to use polluting intermediate goods in production as an input. Consequently, the labor demand in the final goods sector diminishes. As a result, labor shifts from the final goods sector to the R&D sector, resulting in a higher creative destruction rate and, consequently, more economic growth.

Moreover, one can understand this result more rigorously by examining the elasticity of aggregation factors of the production function $\Omega_1(H)$ and intermediate goods demand $\Omega_2(H)$ with respect to the green tax burden H. As expected, these terms decrease with the green tax burden H. An important element explaining how the pollution tax promotes growth is the elasticity of these aggregation terms. We show that the elasticity of the aggregation factor of the production function is higher than the elasticity of the aggregation factor of the intermediate goods factor (see Appendix L). This means that the green tax affects the final goods sector more negatively than the intermediate goods sector. Equivalently, it means that the demand for intermediate goods decreases less than the demand for final goods. This results in a shift of labor from the final goods sector to the R&D sector, which aims to improve the productivity and emission intensity of intermediate goods. We also show that a necessary condition for the positive effect of the pollution tax on growth is that the marginal cost of producing a machine $m = \chi + H$ is below a certain threshold. We have similar results for the recurrent event case as well (see Appendix L for more details).

To assess this effect more clearly, one may examine how labor allocation reacts to a change in the marginal cost of pollution H. As R&D is known to promote growth in the economy when the aforementioned conditions are fulfilled, the graphic[26] shows the effect of the green tax burden H on labor allocation in the R&D sector.

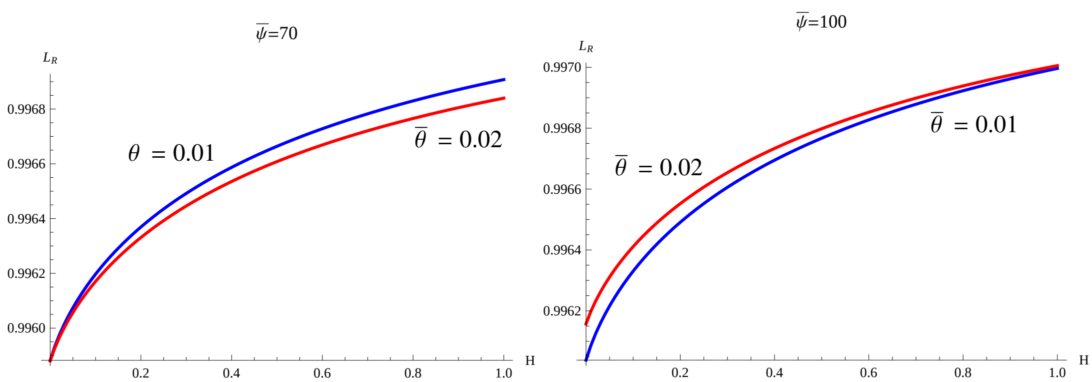


Figure 4: The effect of green tax burden H on labor allocation in R&D (doomsday event) - Blue curve for $\bar{\theta} = 0.01$ and red curve for $\bar{\theta} = 0.02$.

An important point to note is that the R&D sector aims to improve the productivity and emission intensity of intermediate goods. Consequently, the expected value of R&D is proportional to the profit of the monopolist intermediate goods producer (see equation (15)). In this sense, we can argue that if the demand for intermediate goods decreases less than the demand for final goods, there is an expectation that labor will shift from the final goods sector to the R&D sector.

It's worth discussing the relationship between the abrupt event probability $\bar{\theta}$ and the effect of the pollution tax on growth. The positive effect of the pollution tax on growth increases when the penalty rate $\bar{\psi}$ exceeds a certain threshold (see Appendix J). This is due to the fact that the expected value of R&D increases as the interest rate decreases with a higher marginal benefit of R&D. Therefore, in cases where the adaptation effect dominates the discount effect, the positive effect of the pollution tax on growth increases with a higher

[26] The parameter values for the graphic below are as follows: $\rho = 0.05$, $\omega = 0.8$, $\psi = 10$ and 100, $\alpha = 0.3$, $\beta = 0.05$, $\lambda = 0.7$, $\gamma_2 = -0.6$, $\gamma_1 = 0.9$, $H = 0.1$, $\chi = 1$.

abrupt event probability $\bar{\theta}$.

4 Adaptation and Mitigation in a Market Economy

It is interesting to examine how the market economy adapts and mitigates when it faces a higher catastrophe event probability $\bar{\theta}$. To assess the implications of the pollution tax on the adaptation of the economy, one should observe how the value of R&D $V(t)$ changes concerning the catastrophic event probability. Recall that knowledge accumulation, which allows for adaptation, stems from R&D activity. An economy that accumulates knowledge becomes wealthier (see Lemma 1). On the other hand, the mitigation activity can be captured through the variable Z, which stands for the pollution intensity.

Indeed, it is worthwhile to note that the market economy does not explicitly target adaptation and mitigation activities. In our framework, it is clear that adaptation and mitigation activities are promoted by means of R&D activity, which primarily aims to obtain R&D patents that provide dividends to shareholders. Thus, it is plausible to say that the balance between adaptation and mitigation is the natural outcome of R&D in the market. A proxy indicator can be easily constructed to understand how the balance between adaptation and mitigation is found in the market economy.

The variable $M = \frac{1}{Z}$ can be considered as the mitigation activity. As the pollution intensity decreases, mitigation increases. The economy starts to adapt more when the knowledge stock increases. This means that when wealth accumulation a increases, the resilience against a climatic catastrophe increases. The growth rate of adaptation and mitigation is given by

$$g_A = \frac{1}{1-\alpha}\left(\gamma_1 + \gamma_2\right)\lambda L_R,$$

$$g_M = -\gamma_2 \lambda L_R,$$

$$g_{\frac{A}{M}} = \left(\frac{\gamma_1}{1-\alpha} + \left(1 + \frac{1}{1-\alpha}\right)\gamma_2\right)\lambda L_R.$$

Proposition 3. *(i) At the balanced growth path, the growth rate of adaptation is higher than that of mitigation $g_{\frac{A}{M}} > 0$ if the cleanliness rate of R&D respects the condition*

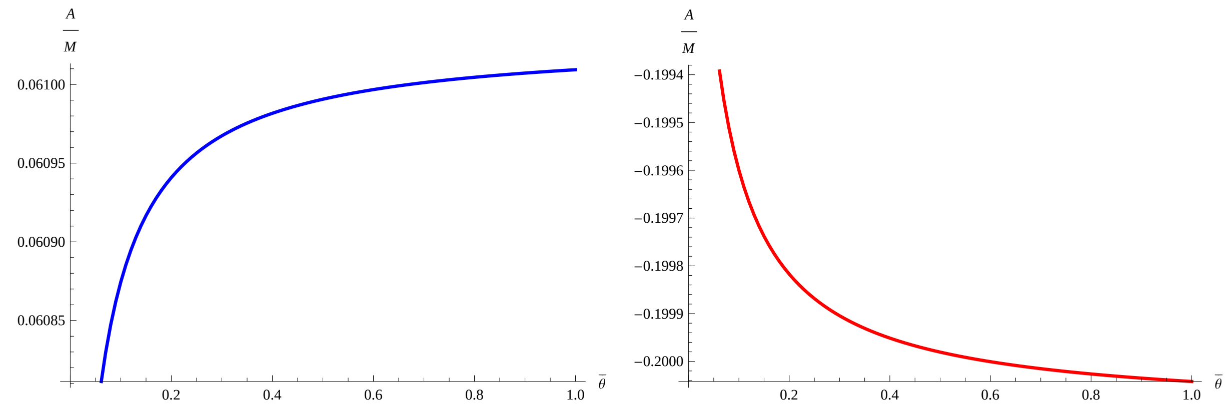
$$-\left(\frac{\gamma_1}{\gamma_2}\right) > 2 - \alpha,$$

otherwise we have $g_{\frac{A}{M}} < 0$.

In cases where $-\left(\frac{\gamma_1}{\gamma_2}\right) > 2 - \alpha$, when the cleanliness rate of R&D γ_2 is not high enough relative to the total productivity γ_1, the growth rate for the adaptation/mitigation ratio $\frac{A}{M}$ is positive. Then, the economy adapts always much more than it mitigates in the long run. In case 2, the economy offers cleaner innovations compared to case 1. Therefore, the growth rate of the adaptation/mitigation ratio is negative, indicating that mitigation is higher than adaptation.

It is interesting to focus on the relation between the catastrophic event probability $\bar{\theta}$ and the equilibrium level of adaptation and mitigation. Taking into consideration Proposition 1, when the economy facing a high-level penalty rate allocates more labor to R&D activities, the growth rate of adaptation is higher than that of mitigation in case $-\left(\frac{\gamma_1}{\gamma_2}\right) > 2 - \alpha$ and vice versa in case $-\left(\frac{\gamma_1}{\gamma_2}\right) < 2 - \alpha$.

We illustrate this result numerically[27]



(a) $g_{\frac{A}{M}} > 0$ with $\left(\frac{\gamma_1}{\gamma_2}\right) > 2 - \alpha$

(b) $g_{\frac{A}{M}} < 0$ with $\left(\frac{\gamma_1}{\gamma_2}\right) < 2 - \alpha$

Figure 5: Growth rate of adaptation/mitigation

As one can see, the economy starts to accumulate more wealth with higher catastrophe probability $\bar{\theta}$ in order to adapt to the penalty due to the catastrophic event. In cases where the penalty rate is not high, the economy would allocate less labor to R&D. Then, the ratio of adaptation to mitigation would fall, indicating that the growth rate of mitigation becomes higher relative to that of adaptation when the economy faces a higher risk of abrupt events.

In Figure (5b), the ratio of total productivity to the cleanliness of R&D $\left(\frac{\gamma_1}{\gamma_2}\right)$ is low. Therefore, the market mitigates more than it adapts to the catastrophic event. Moreover, we observe an interesting result related to adaptation and mitigation activities. When the cleanliness of R&D is higher, economic growth decreases, as R&D offers cleaner intermediate goods that are less productive (see Ricci (2007), Aghion and Howitt (1997)).[28] This leads to a decrease in final good production Y. Then, the growth rate of mitigation comes at the cost of the growth rate of adaptation.

A similar result is also present in Tsur and Zemel (2016a) and Bréchet et al. (2012), but the difference is that in our model, the growth rate of adaptation and mitigation is always positive in the market economy. Consequently, the economy always increases its adaptation and mitigation levels over time. However, in Tsur and Zemel (2016a), Bréchet et al. (2012), and Kama and Pommeret (2016), the trade-off relies on the optimal allocation of resources between adaptation and mitigation. It follows that when the economy invests more in adaptation, this comes at the cost of mitigation investments. Nonetheless, when adaptation and mitigation activities arise as a natural outcome from the R&D sector and both of them grow in the long run, we are not allowed to mention a trade-off between adaptation and mitigation in our framework.

The growth rates of adaptation, mitigation, and pollution in the long run are:

[27] The parameter values for the graphic are as follows: $\rho = 0.05$, $\omega = 0.8$, $\psi = 160$, $\alpha = 0.3$, $\beta = 0.05$, $\lambda = 0.1$, $\gamma_2 = -0.25$, $\gamma_1 = 0.75$, $H = 0.1$, $\chi = 2$ for the first graphic where $-\left(\frac{\gamma_1}{\gamma_2}\right) > 2 - \alpha$. The parameters that change are $\gamma_2 = -0.25$, $\gamma_1 = 0.5$ for the second graphic.

[28] The authors argue that capital-intensive intermediate goods are more productive.

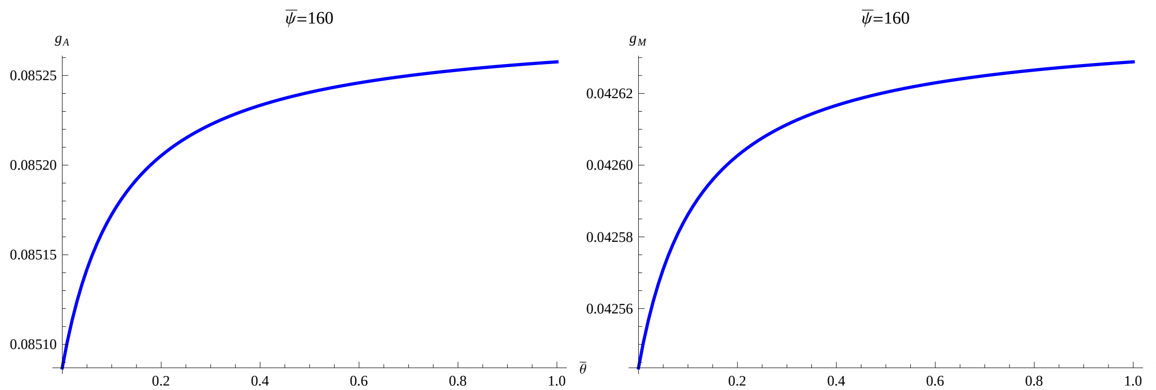


Figure 6: Growth rate of adaptation and mitigation

Keeping in mind that the economy grows and adapts to abrupt events at each date, one may ask how the aggregate pollution evolves in the long run. Despite the relaxation of the trade-off between adaptation and mitigation in a decentralized economy, we show that a new trade-off between R&D activities and pollution arises in the market economy.

Before presenting this trade-off, we write the aggregate pollution

$$P\left(t\right)=\left[\bar{\phi}_{max}\left(t\right)\right]\left[\underline{z}_{min}\left(t\right)\right]^{\frac{1}{\alpha\beta}}Y\left(t\right). \tag{34}$$

It is easy to remark that pollution $P\left(t\right)$ is proportional to aggregate production $Y\left(t\right)$. Differentiating equation (34), in the long run, pollution growth can be written

$$g_P=\left(\frac{2-\alpha}{1-\alpha}g_\phi+\frac{1+\frac{(1-\alpha)}{\alpha\beta}}{1-\alpha}g_Z\right)=\frac{1}{1-\alpha}\left(\left(2-\alpha\right)\gamma_1+\left(1+\frac{(1-\alpha)}{\alpha\beta}\right)\gamma_2\right)\lambda L_R. \tag{35}$$

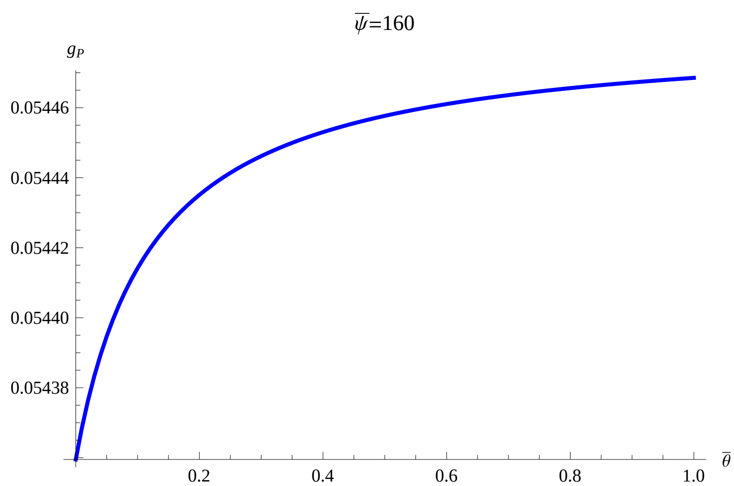


Figure 7: Growth rate of pollution

The numerical exercise confirms that when the economy adapts to abrupt events in the face of higher abrupt event probability, pollution growth is also higher, despite the higher growth rate of mitigation in the long run. This outcome is due to the scale effect mentioned above. In fact, this result challenges the adaptation and mitigation trade-off and reveals a new trade-off between R&D activities and pollution.

Proposition 4: Pollution growth at the balanced growth path is given by

$$g_P > 0 \; if \; -\left(\frac{\gamma_1}{\gamma_2}\right) > \frac{\left(1 + \frac{(1-\alpha)}{\alpha\beta}\right)}{2-\alpha} \tag{36}$$

or

$$g_P < 0 \text{ if } -\left(\frac{\gamma_1}{\gamma_2}\right) < \frac{\left(1 + \frac{(1-\alpha)}{\alpha\beta}\right)}{2-\alpha}. \tag{37}$$

In the market economy, pollution can grow, even in the presence of cleaner intermediate goods, when the economy allocates much more labor to R&D. Indeed, total productivity improvements through R&D activity increase the scale of the economy. Due to the scale effect, pollution growth in the long run turns out to be higher if R&D does not offer sufficiently cleaner intermediate goods. This result can be referred to as Jevons Paradox, which claims that technological improvements increase the efficiency of energy used in production but also increase the demand for energy. In the Schumpeterian economy, the demand for intermediate goods increases with the scale effect. Consequently, pollution growth can be higher even with cleaner intermediate goods.

5 Conclusion

In this paper, our contribution builds on the analysis of adaptation and mitigation through an endogenous R&D process in a decentralized economy. The existing literature treated the adaptation and mitigation policy mix in the social optimum framework without taking into account the presence of endogenous R&D decision-making.

We examine the effect of catastrophe probability on R&D decisions in the market economy. R&D activity aims to improve the total productivity of labor and the emission intensity of intermediate goods. Additionally, R&D serves to adapt to damage from abrupt events as well. We show that a higher abrupt event probability increases R&D if the penalty rate is above a threshold. This result relies on the fact that the marginal benefit of R&D increases since innovation patents help to decrease vulnerability to damage from abrupt events.

Similar to Hart (2004) and Ricci (2007), we show that a pollution tax can promote the growth rate of the economy. However, differently from these studies, the effect of the pollution tax with respect to abrupt event probability is shown to be higher or lower depending on the penalty rate.

The market economy starts to accumulate more knowledge and adapt more if the total productivity of R&D is higher than the cleanliness of innovations. This fact relies on the assumption that cleaner intermediate goods are less productive. Consequently, the growth rate turns out to be lower in the long run. This implies that mitigation comes at the cost of wealth accumulation in the long run. However, in a growing economy in the long run, the trade-off between adaptation and mitigation is not as relevant as claimed in many studies (see Tsur and Zemel (2016a), Zemel (2015)), as adaptation and mitigation both continue to grow in the long run. We demonstrate that a new relationship between adaptation and pollution can emerge. Since wealth accumulation (adaptation) increases the growth rate of the economy in the long run, pollution growth can be higher due to the increased scale of the economy. This result highlights the possibility of a Jevons paradox, where the economy emits more pollution despite using cleaner intermediate goods.

A Production Function

As in Ricci (2007), we define the function as

$$Y(t) = \int_0^1 \left(\phi(v,t) L_Y(t)\right)^{1-\alpha} \left(P(v,t)^{\beta} x(v,t)^{1-\beta}\right)^{\alpha} dv, \tag{A1.1}$$

where $P(v,t)$ is the polluting input. From the production function, we can define a emissions-intermediate good ratio to simplify the production function;

$$z(v,t) = \left(\frac{P(v,t)}{\phi(v,t)^{\frac{1}{\beta}} x(v,t)}\right)^{\alpha\beta}. \tag{A1.2}$$

The production function takes a simpler form

$$Y(t) = L_Y(t)^{1-\alpha} \int_0^1 \phi(v,t) z(v,t) x(v,t)^{\alpha} dv. \tag{A1.3}$$

B An economy facing an uncertain harmful event

Taking the expectations of (17) gives

$$E_T\left[\int_0^T u(c(t)) e^{-\rho t} dt + e^{-\rho T} \varphi(a(T))\right]. \tag{B1.4}$$

Note that the probability distribution and density function are

$$\tilde{f}(t) = \bar{\theta} e^{-\bar{\theta} t} \text{ and } \tilde{F}(t) = 1 - e^{-\bar{\theta} t}. \tag{B1.5}$$

We write the following expression:

$$\int_0^\infty \tilde{f}(T)\left[\int_0^T u(c(t)) e^{-\rho t} dt + e^{-\rho T} \varphi(a(T))\right] dT$$
$$= \underbrace{\int_0^\infty \tilde{f}(T)\left[\int_0^T u(c(t)) e^{-\rho t} dt\right] dT}_{\text{A}} + \underbrace{\int_0^\infty \tilde{f}(T)\left[e^{-\rho T} \varphi(a(T))\right] dT}_{\text{B}}. \tag{B1.6}$$

Integrating by parts, A yields

$$dX = \tilde{f}(T) \implies X = \int_0^T \tilde{f}(s) ds Y = \int_0^T u(c(t)) e^{-\rho t} dt \implies dY = U(c(T)) e^{-\rho T}.$$

Using $\int Y dX = XY - \int X dY$ yields

$$A = \left[\left(\int_0^T \tilde{f}(s) ds\right)\left(\int_0^T u(c(t)) e^{-\rho t} dt\right)\right]_{T=0}^{\infty} - \int_0^\infty \tilde{F}(T) u(c(T)) e^{-\rho T} dT. \tag{B1.7}$$

Recall that $\int_0^\infty \tilde{f}(s) ds = 1$. Part A leads to

$$\int_0^\infty u(c(t)) e^{-\rho t} dt - \int_0^\infty \tilde{F}(t) u(c(t)) e^{-\rho t} dt. \tag{B1.8}$$

Taking the sum $A+B$, it follows that

$$\int_0^\infty \left[\left(1-\tilde{F}(t)\right)u(c(t))+\tilde{f}(t)\varphi(a(T))\right]e^{-\rho t}dt. \tag{B1.9}$$

Thus, inserting the probability distribution and density function gives

$$\int_0^\infty \left[u(c(t))+\bar{\theta}\varphi(a(T))\right]e^{-\left(\rho+\bar{\theta}\right)t}dt. \tag{B1.10}$$

C Proof of Lemma 1

We can reformulate the budget constraint in the form

$$\dot{a}(t)=r(t)a(t)+w(t)-c(t)+R(t). \tag{C1.11}$$

With the perfect competition assumption in final good sector, the profits are equal to zero.

$$c(t)+\chi x(t)=Y(t)=w(t)L_Y(t)+\int_0^1 p(v,t)x(v,t)dv. \tag{C1.12}$$

By replacing zero profit condition (C1.12) in budget constraint of the household (C1.11), the budget constraint becomes

$$\dot{a}(t)=r(t)a(t)+w(t)L_R(t)-\left[\int_0^1 p(v,t)x(v,t)dv-h(t)P(t)-\chi x(t)\right]. \tag{C1.13}$$

From free-entry condition in R&D sector, we know $\lambda L_R(t)V(t)-w(t)L_R(t)=0$. Recall that the term in brackets is the total profit $\pi(t)=\int_0^1 \pi(v,t)dv$ in intermediate good sector. Then, the budget constraint becomes

$$\dot{a}(t)=r(t)a(t)+\lambda L_R(t)V(t)-\pi(t). \tag{C1.14}$$

Consequently, the Hamilton-Jacobi-Bellman equation for expressing the expected value of an innovation in R&D sector allows us to conclude that

$$a(t)=V(t). \tag{C1.15}$$

This completes the proof of Lemma 1.

D Condition on Penalty Function

From the household problem, we define the post-value function as

$$\varphi^D(a(t))=u(c_{min})-\psi(a(t)), \tag{D1.16}$$

and the penalty function

$$\psi(a(t))=\bar{\psi}(\omega-(1-\omega)log(a(t))). \tag{D1.17}$$

At balanced growth path, the post value function can be written in the following manner ;

$$\varphi^{D,*} = -\int_0^\infty \psi\left(a\left(t\right)\right) e^{-\left(\rho+\bar{\theta}\right)t} dt = -\bar{\psi}\left(\frac{\omega}{\rho+\bar{\theta}} - \frac{\left(1-\omega\right) log\left(a\left(0\right)\right)}{\rho+\bar{\theta}-g_Y}\right), \tag{D1.18}$$

and

$$\omega > \frac{\left(\rho+\bar{\theta}\right) ln\left(a\left(0\right)\right)}{\left(\rho+\bar{\theta}\right)\left(1+ln\left(a\left(0\right)\right)\right)-g_Y}, \tag{D1.19}$$

where $a\left(0\right)$ is the level of wealth at the initial date.

E Cross-Sectoral Distribution

E.1 Productivity Distribution

We follow a method similar to Aghion and Howitt (1997) in order to characterize the long-run distribution of relative productivity terms, both for technology improvements $\phi(v,t)$ and emission intensity $z(v,t)$. Let $F(.,t)$ be the cumulative distribution of the technology index ϕ across different sectors at a given date t, and write $\Phi(t) \equiv F(\phi,t)$. Then,

$$\Phi\left(0\right) = 1, \tag{E1.20}$$

$$\frac{\dot{\Phi}\left(t\right)}{\Phi\left(t\right)} = -\lambda L_R\left(t\right). \tag{E1.21}$$

Integrating this equation yields

$$\Phi\left(t\right) = \Phi\left(0\right) e^{-\lambda\gamma_1 \int_0^t L_R(s)ds}. \tag{E1.22}$$

Equation (E1.20) holds because it is not possible that a firm has a productivity parameter ϕ larger than the leading firm in the sector. Equation (E1.21) means that at each date, a mass of λn firms lags behind due to innovations that take place with a Poisson distribution. From equation (12), we can write

$$\frac{\dot{\bar{\phi}}_{max}\left(t\right)}{\bar{\phi}_{max}\left(t\right)} = \gamma_1 \lambda L_R. \tag{E1.23}$$

Integrating equation (E1.23), we have ;

$$\bar{\phi}_{max}\left(t\right) = \bar{\phi}_{max}\left(0\right) e^{\lambda\gamma_1 \int_0^t L_R(s)ds}, \tag{E1.24}$$

where $\bar{\phi}_{max}\left(0\right) \equiv \bar{\phi}$. By using equations (E1.22) and (E1.24), we write

$$\left(\frac{\bar{\phi}}{\bar{\phi}_{max}}\right)^{\frac{1}{\gamma_1}} = e^{-\lambda \int_0^t L_R(s)ds} = \Phi\left(t\right). \tag{E1.25}$$

We define a to be the relative productivity given by $a = \frac{\bar{\phi}}{\bar{\phi}_{max}}$. Essentially, $\Phi(t)$ represents the probability density distribution.

E.2 Emission Intensity Distribution

By proceeding exactly in the same manner, we have

$$\frac{\dot{\underline{z}}_{min}\left(t\right)}{\underline{z}_{min}\left(t\right)} = \gamma_2 \lambda L_R. \tag{E2.26}$$

Integrating equation (E2.26), we obtain

$$\underline{z}_{min}(t) = \underline{z}_{min}(0)\, e^{\lambda\gamma_2 \int_0^t L_R(s)ds}. \tag{E2.27}$$

We can rewrite this equation as

$$\left(\frac{\underline{z}}{\underline{z}_{min}}\right)^{\frac{1}{\gamma_2}} = e^{-\lambda \int_0^t L_R(s)ds}. \tag{E2.28}$$

We can easily observe that this last equation is the same as the one found in equation (E1.25). We write

$$\left(\frac{\bar{\phi}}{\bar{\phi}_{max}}\right)^{\frac{1}{\gamma_1}} = \left(\frac{\underline{z}}{\underline{z}_{min}}\right)^{\frac{1}{\gamma_2}}. \tag{E2.29}$$

From equation (E2.29), we can find the relative distribution for emission intensity across firms:

$$\frac{\underline{z}}{\underline{z}_{min}} = \left(\frac{1}{a}\right)^{-\frac{\gamma_2}{\gamma_1}}.$$

F Aggregate Economy

We replace the equation of the supply of machines (7) in equation (1) and write

$$Y(t) = L_Y(t) \int_0^1 \phi(v,t)z(v,t) \left(\frac{\alpha^2 \phi(v,t)z(v,t)}{\chi + h(t)\phi(v,t)^{\frac{1}{\beta}} z(v,t)^{\frac{1}{\alpha\beta}}}\right)^{\frac{\alpha}{1-\alpha}} dv. \tag{F1.30}$$

We proceed to reformulate the production in a way that allows us to express productivity and emission intensity gaps. Note that, according to Aghion and Howitt (1997), these gaps are constant over time. By dividing and multiplying the numerator and denominator by $\bar{\phi}_{max}\underline{z}_{min}$, we get

$$Y(t) = \alpha^{\frac{2\alpha}{1-\alpha}} L_Y(\bar{\phi}_{max}(t)\underline{z}_{min}(t))^{\frac{1}{1-\alpha}} \int_0^1 \left[\left(\frac{\phi(v,t)}{\bar{\phi}_{max}}\frac{z(v,t)}{\underline{z}_{min}}\right)^{\frac{1}{1-\alpha}} \left(\frac{1}{\left(\chi + h(t)\bar{\phi}_{max}^{\frac{1}{\beta}}\underline{z}_{min}^{\eta}\left(\frac{z(v,t)}{\underline{z}_{min}}\right)^{\frac{1}{\alpha\beta}}\frac{\phi(v,t)}{\bar{\phi}_{max}}\right)}\right)^{\frac{\alpha}{1-\alpha}} dv\right]. \tag{F1.31}$$

Using the productivity and emission intensity distributions, we find the aggregate production function as follows:

$$Y(t) = \frac{\gamma_1}{1-\gamma_1}\alpha^{\frac{2\alpha}{1-\alpha}} L_Y(\bar{\phi}_{max}(t)\underline{z}_{min}(t))^{\frac{1}{1-\alpha}}\Omega_1(H), \tag{F1.32}$$

where the aggregation function for production $\Omega_1(H)$ is given by:

$$\Omega_1(H) = \int_0^1 \frac{a^{\frac{1}{1-\alpha}\left(1+\frac{\gamma_2}{\gamma_1}\right)}}{\left(1+\frac{H}{\chi}a^{\frac{1}{\beta}+\frac{\gamma_2}{\gamma_1}\frac{1}{\alpha\beta}}\right)^{\frac{\alpha}{1-\alpha}}}\nu'(a)da, \tag{F1.33}$$

where $H = h(t)\bar{\phi}_{max}\underline{z}_{min}^{\eta}$, which is a constant term over time by the policy rule, and $\nu'(a)$ is the density function for the function $\nu(a) = F(.,t) = a^{\frac{1}{\gamma_1}}$.

The aggregation of the intermediate factor $x(t)$ is obtained in the same manner:

$$x(t) = \int_0^1 x(v,t)dv = \frac{\gamma_1}{1-\gamma_1}\alpha^{\frac{2}{1-\alpha}} L_Y(\bar{\phi}_{max}(t)\underline{z}_{min}(t))^{\frac{1}{1-\alpha}}\Omega_2(H), \tag{F1.34}$$

where the aggregation factor $\Omega_2(H)$ for the intermediate good $x(t)$ is:

$$\Omega_2(H) = \int_0^1 \frac{a^{\frac{1}{1-\alpha}\left(1+\frac{\gamma_2}{\gamma_1}\right)}}{\left(1+\frac{H}{\chi}a^{\frac{1}{\beta}+\frac{\gamma_2}{\gamma_1}\frac{1}{\alpha\beta}}\right)^{\frac{1}{1-\alpha}}}\nu'(a)da. \tag{F1.35}$$

The final good market equilibrium yields $Y(t) = c(t) + \chi x(t)$, since some part of the final good is used for the production of the intermediate good. From equation (6), we know that the aggregate cost of the production good $x(t)$ is given by $\chi x(t)$.

$$c(t) = Y(t) - \chi x(t) = \left(1 - \alpha^2\frac{\Omega_2(H)}{\Omega_1(H)}\right)Y(t). \tag{F1.36}$$

This equation gives the consumption $c(t)$ as a function of the production function $Y(t)$.

G Aggregation Factor

From the production function, in order to solve the integral (F1.33), we have

$$\Omega_1(H) = \int_0^1 \frac{a^{\bar{\gamma}}}{\left(1+\frac{H}{\chi}a^{\frac{1}{\beta}+\frac{\gamma_2}{\gamma_1}}\right)^{\frac{\alpha}{1-\alpha}}}da, \tag{G1.37}$$

where $\bar{\gamma} = \frac{1}{1-\alpha}\left(1+\frac{\gamma_2}{\gamma_1}\right) + \frac{1}{\gamma_1} - 1$. We use the substitution method. We define

$$y = -\frac{H}{\chi}a^{\frac{1}{\beta}+\frac{\gamma_2}{\gamma_1}\frac{1}{\alpha\beta}}, \quad dy = -\left(1+\frac{\gamma_2}{\gamma_1}\right)\frac{H}{\chi}a^{\frac{1}{\beta}+\frac{\gamma_2}{\gamma_1}\frac{1}{\alpha\beta}-1}da. \tag{G1.38}$$

We rewrite the aggregation factor as

$$\Omega_1(H) = -\int_{-\frac{H}{\chi}}^0 y^{\frac{\bar{\gamma}+1-b}{b}}(1-y)^{-\frac{\alpha}{1-\alpha}}dy, \tag{G1.39}$$

where $b = \frac{1}{\beta} + \frac{\gamma_2}{\gamma_1}\frac{1}{\alpha\beta}$. It is easy to see that the expression in the integral is the incomplete beta function. Then, we can express this integral using the Gaussian hypergeometric function as follows:

$$\Omega_1(H) = \left(\frac{1}{1+\bar{\gamma}}\right){}_2F_1\left(\frac{\bar{\gamma}+1}{b}, \frac{\alpha}{1-\alpha}; \frac{\bar{\gamma}+b+1}{b}; -\frac{H}{\chi}\right). \tag{G1.40}$$

To see the marginal change of the aggregation factor with respect to the marginal cost of pollution H:

$$\frac{\partial\Omega_1(H)}{\partial H} = -\frac{1}{\chi}\left(\frac{\alpha(\bar{\gamma}+1)}{(1-\alpha)(\bar{\gamma}+1+b)}\right){}_2F_1\left(\frac{\bar{\gamma}+1}{b}+1, \frac{\alpha}{1-\alpha}+1; \frac{\bar{\gamma}+b+1}{b}+1; -\frac{H}{\chi}\right) < 0.$$

H Household's Maximization Program

The Hamilton-Jacobi-Bellman equation is (by dropping the time index):

$$\rho W^B(a) = \max_c \left\{u(c) + W_a^B(ra - w - c + R) + \bar{\theta}(W^B(a) - \varphi(a))\right\}, \tag{H1.41}$$

where $W^B(a)$ is the value function before the uncertain harmful event, and $\varphi(a)$ is the post-value function. We consider two different post-value functions:

1. For recurrent events:

$$\varphi(a) = W^B(a) - \psi(a). \tag{H1.42}$$

The dynamics of the system do not change, but the economy is exposed to a penalty that is proportional to the capital level a.

2. For the doomsday event:

$$\varphi(a) = u(c_{min}) - \psi(a), \tag{H1.43}$$

where $u(c_{min})$ is the utility level that may be normalized to zero, similar to Bommier et al. (2015); Tsur and Zemel (2016b).

For the doomsday event case, the first-order condition is:

$$u_c(c) = V_a(a). \tag{H1.44}$$

The envelope condition is:

$$\rho W_a^B(a) = W_{aa}^B(a)\dot{a} + rW_a^B(a) + \theta\psi_a(a). \tag{H1.45}$$

Then, it is possible to write the Keynes-Ramsey equation using the utility function $u(c) = \log c$:

$$\frac{\dot{c}}{c} = \left(r - (\rho + \bar{\theta}) + \bar{\theta}\frac{\psi_a(a)}{u_c(c)} \right). \tag{H1.46}$$

The Keynes-Ramsey equation with the recurrent-event case is:

$$\frac{\dot{c}}{c} = \left(r - \rho + \bar{\theta}\frac{\psi_a(a)}{u_c(c)} \right). \tag{H1.47}$$

The crucial difference is that the probability $\bar{\theta}$ cancels out with recurrent events.

I Labor Allocation in Equilibrium

To find the labor allocation in R&D sector, we differentiate equation (15), which yields the Hamilton-Jacobi-Bellman equation at the balanced growth path:

$$(r + \lambda L_R) - \frac{\dot{V}(t)}{V(t)} = \frac{\pi(\bar{\phi}_{max}, \underline{z}_{min})}{V(t)}. \tag{I1.48}$$

Lemma 1 shows that the household owns the firms in the market, and the household receives dividends from innovation assets on the market.

Using the functional forms defined in the text and the resource constraint $Y(t) = c(t) + \chi x(t)$, the growth rate of the economy can be written as:

$$g_c = \frac{\dot{c}(t)}{c(t)} = r(t) - (\rho + \bar{\theta}) + \frac{\lambda\bar{\theta}\bar{\psi}(1-\omega)}{(1-\alpha)}\left(1 - \frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)L_Y. \tag{I1.49}$$

Note that by the free-entry condition, we have $g_V = g_w = g_Y$. Using equations (I1.49) and (9), we reformulate the expected value of an innovation:

$$\left(\frac{1}{1-\alpha}(g_\phi + g_Z) + (\rho+\bar{\theta}) - \frac{\bar{\theta}\bar{\psi}(1-\omega)}{\lambda(1-\alpha)}\left(1-\frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)(1-L_R)+\lambda L_R\right)$$
$$= \left(\frac{\alpha\gamma_1}{\lambda(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)}(1-L_R)\right) = \frac{\pi(\bar{\phi}_{max}, \underline{z}_{min})}{V(t)}. \tag{I1.50}$$

From (I1.50), we can find the equilibrium level of labor in the R&D sector (see equation (29)).

J Proof of Proposition 1

To assess the impact of a doomsday catastrophe probability on labor in R&D, we take the derivative of L_R (equation (29)) with respect to hazard rate $\bar{\theta}$;

$$\frac{\partial L_R}{\partial \bar{\theta}} = \frac{\frac{\gamma_1+\gamma_2}{1-\alpha} + \rho - \frac{\alpha\lambda\gamma_1}{(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)} + \lambda\left(\frac{\lambda(1-\omega)\bar{\psi}}{1-\alpha}\left(1-\frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)-1\right)}{\left[\frac{\gamma_1+\gamma_2}{1-\alpha}+\rho-\lambda-\frac{\alpha\lambda\gamma_1}{(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)} - \frac{\lambda(1-\omega)\bar{\theta}\bar{\psi}}{1-\alpha}\left(1-\frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)\right]^2}. \tag{J1.51}$$

The impact depends whether the penalty rate $\bar{\psi}$ is sufficiently high or not.

$$sign\left(\frac{\partial L_R}{\partial \bar{\theta}}\right) > 0$$

$$\text{if } \bar{\psi} > \frac{\frac{\alpha\gamma_1}{\lambda(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)} + \lambda\left(1-\frac{\gamma_1+\gamma_2}{1-\alpha}\right)}{\left(\frac{\gamma_1+\gamma_2}{1-\alpha}+\rho\right)+\lambda\left(1-\frac{\gamma_1+\gamma_2}{1-\alpha}\right)\frac{\lambda(1-\omega)}{1-\alpha}\left(1-\frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)}. \tag{J1.52}$$

$$sign\left(\frac{\partial L_R}{\partial \bar{\theta}}\right) < 0$$

$$\text{if } \bar{\psi} < \frac{\frac{\alpha\gamma_1}{\lambda(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)} + \lambda\left(1-\frac{\gamma_1+\gamma_2}{1-\alpha}\right)}{\left(\frac{\gamma_1+\gamma_2}{1-\alpha}+\rho\right)+\lambda\left(1-\frac{\gamma_1+\gamma_2}{1-\alpha}\right)\frac{\lambda(1-\omega)}{1-\alpha}\left(1-\frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)}. \tag{J1.53}$$

In the case with recurrent events, we have

$$\frac{\partial L_R^R}{\partial \bar{\theta}} = \frac{\frac{1-\lambda}{1-\alpha}(\gamma_1+\gamma_2)+\rho+\lambda}{\left(\lambda\left(\frac{\gamma_1+\gamma_2}{1-\alpha}-1\right)-\mathit{\Psi}_1-\bar{\theta}\mathit{\Psi}_2\right)^2} > 0,$$

where $\mathit{\Psi}_1 = \frac{\alpha\lambda\gamma_1}{(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)}$, and $\mathit{\Psi}_2 = \frac{\lambda(1-\omega)\bar{\psi}}{1-\alpha}\left(1-\frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)$. It is evident that the catastrophe probability always boosts the creative destruction rate in the economy.

For the part iii) of the proposition, the impact of the catastrophic event probability on the labor allocated to R&D is given by

$$\frac{\partial L_R}{\partial \bar{\theta}} = \frac{\frac{\gamma_1+\gamma_2}{1-\alpha} + \rho - \frac{\alpha\lambda\gamma_1}{(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)} + \lambda\left(\frac{\lambda(1-\omega)\bar{\psi}(1-\Delta)}{1-\alpha}\left(1-\frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)-1\right)}{\left[\frac{\gamma_1+\gamma_2}{1-\alpha}+\rho-\lambda-\frac{\alpha\lambda\gamma_1}{(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)} - \frac{\lambda(1-\omega)\bar{\theta}\bar{\psi}}{1-\alpha}\left(1-\frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)\right]^2}.$$

Then, keeping the same condition for $\bar{\psi}$, we have $sign\left(\frac{\partial L_R}{\partial \bar{\theta}}\right) < 0$ if

$$\text{if}\quad \Delta > 1 - \frac{1}{\bar{\psi}} \frac{\frac{\Psi_1}{\lambda^2} + \lambda\left(1 - \frac{\gamma_1+\gamma_2}{1-\alpha}\right)}{\left(\frac{\gamma_1+\gamma_2}{1-\alpha} + \rho\right) + \lambda\left(1 - \frac{\gamma_1+\gamma_2}{1-\alpha}\right)\Psi_2}.$$

K Marginal Cost of Using Intermediate Good

We know that the marginal cost of using a given machine v is the following:

$$m(v,t) = \chi + H(v,t), \tag{K1.54}$$

where $H(v,t) = h(t)\phi(v,t)z(v,t)^{\frac{1}{\alpha\beta}}$. It is possible to represent equations (E2.28) and (E2.29) in terms of their vintage v,

$$\left(\frac{\bar{\phi}_{\max}(t-v)}{\bar{\phi}_{\max}(v)}\right)^{\frac{1}{\gamma_1}} = e^{-\lambda\int_0^v L_R(s)ds}, \tag{K1.55}$$

$$\left(\frac{\underline{z}_{\min}(t-v)}{\underline{z}_{\min}(v)}\right)^{\frac{1}{\gamma_2}} = e^{-\lambda\int_0^v L_R(s)ds}, \tag{K1.56}$$

Using equations (K1.55) and (K1.56), we find the equation

$$m(v) = \chi + e^{\left(\frac{g_Z}{\alpha\beta}+g_\phi\right)v}H. \tag{K1.57}$$

L Proof of Proposition 2

Taking the derivative of L_R (equation (29)) with respect to marginal cost of pollution H ;

$$\frac{\partial L_R^D}{\partial H} = \frac{\left[a - b + (1-\theta)\Psi_2\right]Z_1 + \left[a + (1-\theta)b - (1-\theta)\Psi_1\right]Z_2}{\left(b - \alpha\Psi_2 - \Psi_1\right)^2} > 0, \tag{L1.58}$$

where

$$Z_1 = \frac{\lambda(1-\omega)\alpha^2\bar{\theta}\bar{\psi}}{(1-\alpha)}\left[\frac{\partial\Omega_2(H)}{\partial H}\frac{1}{\Omega_2(H)} - \frac{\Omega_2(H)}{(\Omega_1(H))^2}\frac{\partial\Omega_1(H)}{\partial H}\right],$$

$$Z_2 = \frac{\alpha\gamma_1\lambda}{(1-\gamma_1)}\left[-\frac{\partial\Omega_1(H)}{\partial H(\Omega_1(H))^2} - \frac{\alpha}{1-\alpha}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}-1}}{\Omega_1(H)}\right],$$

$$\Psi_1 = \frac{\alpha\lambda\gamma_1}{(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)},$$

$$\Psi_2 = \frac{\lambda(1-\omega)\bar{\psi}}{1-\alpha}\left(1 - \frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right),$$

with $a = \left(\frac{\gamma_1+\gamma_2}{1-\alpha} + \rho\right)$ and $b = \lambda\left(\frac{\gamma_1+\gamma_2}{1-\alpha} - 1\right)$. The parameters in front of Z_1 and Z_2 are both positive. The impact of pollution tax depends on the relationship between elasticity of aggregation factor of production $\Omega_1(H)$ and that of intermediate good demand. The increase of marginal cost of pollution increases labor allocation in R&D if

Condition 1.

$$-\frac{\frac{\partial \Omega_1(H)}{\Omega_1(H)}}{\frac{\partial H}{H}} > -\frac{\frac{\partial \Omega_2(H)}{\Omega_2(H)}}{\frac{\partial H}{H}}. \tag{L1.59}$$

A necessary condition to have a positive impact of pollution tax on growth is that the elasticity of aggregation factor of production function is higher than the elasticity of aggregation factor of intermediate good factor. We know that a higher marginal pollution tax implies a lower production of final good which follows a lower intermediate good demand. Then, the term Z_1 is positive.

Condition 2.

$$H + \chi < 2. \tag{L1.60}$$

In order to ensure that Z_2 is positive, we impose some conditions on some key parameters of the model. We suppose that $\frac{\bar{\gamma}+1}{b} = 0$ and $\alpha = \frac{1}{3}$. Our purpose in doing this is to gain insight about the mechanism that explains why a higher marginal cost of pollution can boost the economic growth at the long run. If the producing cost of machines is sufficiently low and the Condition 1. is ensured, the nominator is positive. Consequently, the effect of pollution tax is positive on growth. Note that one of the conditions may not hold and $\frac{\partial L_R}{\partial H}$ may be positive. In this case, one should compare the parameters in front of Z_1 and Z_2.

For the recurrent events, we find

$$\frac{\partial L_R^R}{\partial H} = \frac{\left(\frac{1-\lambda}{1-\alpha}(\gamma_1+\gamma_2)+\lambda\right)\left(\bar{\theta} Z_1 + Z_2\right)}{\left(b - \alpha \varPsi_2 - \varPsi_1\right)^2}. \tag{L1.61}$$

Then, depending on the sign of Z_1 and Z_2 and the probability of an harmful event recurring, the pollution tax increases or decreases the creative destruction rate in the economy. If both Z_1 and Z_2 are positive, then, the pollution tax always increases the creative destruction rate and vice versa when Z_1 and Z_2 are both negative.

In case $Z_1 > 0$ and $Z_2 < 0$, a higher harmful event probability $\bar{\theta}$ make the L_R^R more likely to increase with a higher pollution tax H, which is due to the elasticity of the aggregation factor with respect to the pollution tax H. On the other hand, if $Z_1 < 0$ and $Z_2 > 0$, a higher harmful event probability $\bar{\theta}$ make the L_R^R more likely to decrease with a higher pollution tax H.

For the doomsday event, to assess the impact of hazard rate on the effect of environmental taxation, we compute

$$\frac{\partial}{\partial \bar{\theta}}\left(\frac{\partial L_R}{\partial H}\right) = k\left(\frac{\left[(1-2\theta)\frac{\lambda\alpha^2(1-\omega)\bar{\psi}}{1-\alpha}\left(1-\frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)\right]Z_1 + \Upsilon_1 Z_2 + \Upsilon_2 \frac{\partial Z_1}{\partial \bar{\theta}}}{k^3}\right) + \frac{\varUpsilon_4 \frac{\lambda\alpha^2(1-\omega)\bar{\psi}}{1-\alpha}\left(1-\frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)}{k^3}, \tag{L1.62}$$

where $k = b - \frac{\lambda\alpha^2(1-\omega)\bar{\theta}\bar{\psi}}{1-\alpha}\left(1-\frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right) - (1-\gamma_1)\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)}$ and $\Upsilon_1 = \frac{\alpha\gamma_1\lambda}{(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)} - b$, $\Upsilon_2 = \left[a - b + (1-\theta)\frac{\lambda\alpha^2(1-\omega)\bar{\theta}\bar{\psi}}{1-\alpha}\left(1-\frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)\right]$, $\varUpsilon_3 = \left[a + (1-\theta)b - (1-\theta)\frac{\alpha\gamma_1\lambda}{(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)}\right]$ and let the numerator of the term (L1.58) $\varUpsilon_4 = \Upsilon_2 + \left[a + (1-\theta)b - (1-\theta)\frac{\alpha\gamma_1\lambda}{(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)}\right]Z_2$.

It is easy but very tedious to find a precise threshold for $\bar{\psi}$ after which the sigh of $\frac{\partial}{\partial \bar{\theta}}\left(\frac{\partial L_R}{\partial H}\right)$ flips since the numerator in (L1.62) may be considered as a cubic equation as a function of $\bar{\psi}$. To show that there exists a threshold for the penalty rate $\bar{\psi}$, we look at $\lim_{\bar{\psi}\to 0}\frac{\partial}{\partial \bar{\theta}}\left(\frac{\partial L_R}{\partial H}\right)$ and $\lim_{\bar{\psi}\to\infty}\frac{\partial}{\partial \bar{\theta}}\left(\frac{\partial L_R}{\partial H}\right)$.

It is easy to show that

$$\lim_{\bar{\psi}\to\infty} \frac{\partial}{\partial\bar{\theta}} \left(\frac{\partial L_R}{\partial H}\right) = +\infty,$$

since the term $k\left[(1-2\theta)\frac{\lambda\alpha^2(1-\omega)\bar{\psi}}{1-\alpha}\left(1-\frac{\alpha^2\Omega_2(H)}{\Omega_1(H)}\right)\right]Z_1 > 0$ where it is the term implying $\left(\bar{\psi}\right)^3$. Then, we have

$$\lim_{\bar{\psi}\to 0} \frac{\partial}{\partial\bar{\theta}} \left(\frac{\partial L_R}{\partial H}\right) = \frac{\Upsilon_1 Z_2}{b-(1-\gamma_1)\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)}} < 0,$$

if $\Upsilon_1 < 0$ and the condition 2. holds (implying $Z_2 > 0$). The denominator is unambiguously positive since the term $k > 0$. This means that, there exists a threshold $g(.)$ for $\bar{\psi}$ such that

$$sign\left(\frac{\partial}{\partial\bar{\theta}}\left(\frac{\partial L_R}{\partial H}\right)\right) > 0 \; if \; \bar{\psi} > g(.), \tag{L1.63}$$

$$sign\left(\frac{\partial}{\partial\bar{\theta}}\left(\frac{\partial L_R}{\partial H}\right)\right) < 0 \; if \; \bar{\psi} < g(.). \tag{L1.64}$$

where $g(.)$ is the positive root of the third degree equation $f\left(\bar{\psi}\right)$.

M Alternative framework: adaptation capital

In this subsection, all the mathematical parts in different sections regarding the final good sector, intermediate good sector, R&D sector remain the same as in the main text. The only difference is about the household's maximization program where there is a capital accumulation process. Lemma 1 shows that the household owns the firms in the market. So, to ease the resolution, we say that the household directly invests in specific adaptation capital, which may take the form of buying assets of firms offering adaptation solutions in the stock market.

We analyze a case where there is a specific adaptation investment $A(t)$ and adaptation capital $K_A(t)$ besides the knowledge capital $a(t)$ which serves as an adaptation measure in the main text. Note that there are some limits due to tractability concerns. We use a linear penalty function $\psi(K_A) = \bar{\psi}(1-K_A)$ where K_A is the specific adaptation capital, and the cost of the adaptation does not enter into the budget constraint but has been taken as a disutility, similar to Zemel (2015). Also, there is linearity between the control variable A for adaptation and the state dynamics. However, we can capture the trade-off between the adaptation expenditure and the consumption (hence the final good production), which is crucial to understand the role of the harmful event probability on the R&D activities.

The economy accumulates adaptation capital $K_A(t)$ over time as follows (dropping the time index):

$$\dot{K}_A = A - \delta K_A, \tag{M1.65}$$

where A is the investment decision in adaptation capital at each time t, which is a control variable, and δ is the depreciation rate of the adaptation capital. Then, the budget constraint is written as follows:

$$\dot{a} = ra - w - c + R. \tag{M1.66}$$

Due to the uncertain harmful events, the economy is exposed to a penalty rate (damage) $\psi(K_A)$ at each time when the harmful event occurs. We suppose $\psi'(K_A(t)) < 0$, meaning that adaptation capital helps to decrease the damage. The post-value function with recurrent harmful events is (dropping the time index):

$$\varphi(K_A, a) = W^B(K_A, a) - \psi(K_A). \tag{M1.67}$$

Investing in adaptation capital has the cost $C(A) = \phi A$ where ϕ is the unit cost parameter, which is expressed in terms of disutility. The Hamilton-Jacobi-Bellman equation is (by abusing notation):

$$\rho W^B = \max_{c,A} \left\{ u(c) - \phi A + W_a^B[ra - w - c + R] + W_{K_A}^B[A - K_A] - \bar{\theta}(W^B - \varphi) \right\}, \tag{M1.68}$$

where $W^B - \varphi = \psi(K_A)$. Note that the first-order conditions are:

$$u_c(c) = W_a^B(K_A, a).$$

The cost of the adaptation ϕA does not enter in the budget constraint. This does not mean that the cost does not change the trade-off between consumption and adaptation investment. The trade-off is clear through the marginal first-order condition $u_c(c) = W_a^B(K_A, a)$. We also have:

$$A = \begin{cases} 0 & \text{if } \frac{\phi}{W_{K_A}^B(K_A,a)} < 1, \\ A^S & \text{if } \frac{\phi}{W_{K_A}^B(K_A,a)} = 1, \\ \bar{A} & \text{if } \frac{\phi}{W_{K_A}^B(K_A,a)} > 1, \end{cases}$$

where A^S is the singular rate for adaptation. The discontinuity of adaptation A is due to the linear dependence of the dynamics of the state variable (M1.65) and the linear cost function for adaptation. We have a singular control problem. We will show further that the singular control makes this alternative modeling of adaptation tractable. The envelope conditions are (by abusing notation):

$$\rho = \frac{W_{aa}^B}{W_a^B}\dot{a} + r + \frac{W_{aK_A}^B}{W_a^B}\dot{K}_A, \tag{M1.69}$$

and

$$\rho = \frac{W_{aK_A}^B}{W_{K_A}^B}\dot{a} + \frac{W_{K_AK_A}^B}{W_{K_A}^B}\dot{K}_A - \delta - \frac{\bar{\theta}\psi_{K_A}}{W_{K_A}^B}. \tag{M1.70}$$

We differentiate the first-order conditions:

$$\frac{u_{cc}}{u_c}\dot{c} = \frac{W_{aa}^B}{W_a^B}\dot{a} + \frac{W_{aK_A}^B}{W_a^B}\dot{K}_A. \tag{M1.71}$$

The singular rate A^S implies $\phi = W_{K_A}^B(K_A, a)$. Differentiating this term gives:

$$\frac{W_{aK_A}^B}{W_{K_A}^B}\dot{a} + \frac{W_{K_AK_A}^B}{W_{K_A}^B}\dot{K}_A = 0. \tag{M1.72}$$

Along the singular curve for the adaptation, equation (M1.72) always holds. We can rewrite (M1.69) and (M1.70) as follows:

$$\frac{u_{cc}}{u_c}\dot{c} = \rho - r,$$

and

$$\rho = -\delta - \frac{\bar{\theta}\psi_{K_A}}{W_{K_A}^B}.$$

To have a tractable model, we simply suppose $\psi(K_A) = \bar{\psi}(1 - K_A)$ where the adaptation capital decreases the damage linearly. The term $\bar{\psi}$ is the constant amount of damage that is supposed to be known. As in the main text, we take a log-utility $u(c) = \log c$.

Then, we have

$$g_c = \frac{\dot{c}}{c} = r - \rho,$$

$$\rho = \frac{\bar{\theta}\bar{\psi}}{\phi} - \delta.$$

We can see that the rate of pure time preference is proportional to the level of the penalty and the harmful event probability. Along the singular curve for the adaptation, we have the dynamics of the consumption at the balanced growth path

$$g_c = r - \left(\frac{\bar{\theta}\bar{\psi}}{\phi} - \delta\right) = \frac{\lambda}{1-\alpha}(\gamma_1 + \gamma_2).$$

Then,

$$r = \frac{\lambda}{1-\alpha}(\gamma_1 + \gamma_2) + \frac{\bar{\theta}\bar{\psi}}{\phi} - \delta.$$

we reformulate the expected value of an innovation

$$\underbrace{\frac{\lambda}{1-\alpha}(\gamma_1 + \gamma_2) + \frac{\bar{\theta}\bar{\psi}}{\phi} - \delta + \lambda L_R}_{=\text{r}+\lambda L_R} - \underbrace{\frac{\lambda L_R}{1-\alpha}(\gamma_1 + \gamma_2)}_{=\frac{\dot{V}(t)}{V(t)}}.$$

$$= \underbrace{\frac{\alpha\gamma_1}{\lambda(1-\gamma_1)}\frac{(\chi + H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)}(1 - L_R)}_{=\frac{\pi(\bar{\phi}_{max}, \underline{z}_{min})}{V(t)}}. \tag{M1.73}$$

Then, the labor allocation in R&D sector at the equilibrium is

$$L_R = \frac{\frac{\lambda}{1-\alpha}(\gamma_1 + \gamma_2) - \frac{\alpha\gamma_1}{\lambda(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)} + \left(\frac{\bar{\theta}\bar{\psi}}{\phi} - \delta\right)}{\frac{\lambda}{1-\alpha}(\gamma_1 + \gamma_2) - \frac{\alpha\gamma_1}{\lambda(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)}}.$$

It is easy to show that

$$\begin{cases} \frac{\partial L_R}{\partial \theta} > 0 & \text{if } \frac{\lambda}{1-\alpha}(\gamma_1 + \gamma_2) > \frac{\alpha\gamma_1}{\lambda(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)}, \\ \frac{\partial L_R}{\partial \theta} < 0 & \text{if } \frac{\lambda}{1-\alpha}(\gamma_1 + \gamma_2) < \frac{\alpha\gamma_1}{\lambda(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)}. \end{cases}$$

Recall that $\frac{\alpha\gamma_1}{\lambda(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)} = \frac{\pi(\bar{\phi}_{max}, \underline{z}_{min})}{V(t)}$, $\frac{\lambda}{1-\alpha}(\gamma_1 + \gamma_2) = \lambda g_Y$ and $g_c = r - \left(\frac{\bar{\theta}\bar{\psi}}{\phi} - \delta\right)$, Then, this means that a higher growth rate than the R&D sector's profit increases the labor allocation in R&D sector with a higher harmful event probability$\bar{\theta}$. The underlying mechanism is as follows: a higher $\bar{\theta}$ is expected to decrease g_c. It follows that the final good producer needs less labor. Hence, the labor shifts to the R&D sector.

In the case of doomsday event, the labor allocation in R&D sector at the equilibrium is

$$L_R = \frac{\frac{\lambda}{1-\alpha}(\gamma_1 + \gamma_2) - \frac{\alpha\gamma_1}{\lambda(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)} + \left(\frac{\bar{\theta}\bar{\psi}}{\phi} - \delta\right) - \bar{\theta}}{\frac{\lambda}{1-\alpha}(\gamma_1 + \gamma_2) - \frac{\alpha\gamma_1}{\lambda(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)}}.$$

It is easy to show that

$$\begin{cases} \frac{\partial L_R}{\partial \theta} > 0 & \text{if } \frac{\lambda}{1-\alpha}\left(\gamma_1+\gamma_2\right) > \frac{\alpha\gamma_1}{\lambda(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)} \text{ and } \bar{\psi} > \phi, \\ \frac{\partial L_R}{\partial \theta} < 0 & \text{if } \frac{\lambda}{1-\alpha}\left(\gamma_1+\gamma_2\right) > \frac{\alpha\gamma_1}{\lambda(1-\gamma_1)}\frac{(\chi+H)^{-\frac{\alpha}{1-\alpha}}}{\Omega_1(H)} \text{ and } \bar{\psi} < \phi. \end{cases}$$

In the case of doomsday event, the amount of the damage matters for the result. The result is quite intuitive; if the amount of the damage is higher than cost of investing in adaptation, then a higher catastrophe probability increases the labor allocation in the R&D sector. The mechanism is quite similar to the previous case. Note that we have $g_c = r - \left(\frac{\bar{\theta}\bar{\psi}}{\phi} - \delta\right) + \bar{\theta}$. With $\bar{\psi} > \phi$, the growth rate is lower, meaning that the labor shifts to the R&D sector.

N Endogenous hazard rate

We show that an increasing hazard rate is important during the transition but not at the balanced growth path. To see this, we let that the harmful event probability is endogenous on the pollution flow $P(t)$ (see Yanase (2011)). We write the following maximization program

$$\rho W^B(a) = \max_c \left\{u(c) + W_a^B(ra - w - c + R) + \theta(P)\left(W^B(a) - \varphi(a)\right)\right\}, \tag{M1.74}$$

where the catastrophic event probability is endogenous on the pollution flow P. Since the pollution flow stems from the production of the final good Y, by using (F1.36), we can write

$$P = \left[\bar{\phi}_{max}\right]\left[\underline{z}_{min}\right]^{\frac{1}{\alpha\beta}} Y = \frac{\left[\bar{\phi}_{max}\right]\left[\underline{z}_{min}\right]^{\frac{1}{\alpha\beta}}}{\left(1-\alpha^2\frac{\Omega_2(H)}{\Omega_1(H)}\right)} c = f(c). \tag{M1.75}$$

Suppose also that the economy is under the risk of recurrent uncertain harmful events which imply $\varphi(a) = W^B(a) - \psi(a)$. We use the following functional form for the endogenous hazard rate

$$\theta(P) = \bar{\theta} - \left(\bar{\theta} - \underline{\theta}\right)e^{-bP}. \tag{M1.76}$$

Then, the first order and the envelop condition are

$$u_c = W_a^B - bf'(c)\left(\left(\bar{\theta} - \underline{\theta}\right)e^{-bf(c)}\right), \tag{M1.77}$$

and

$$\rho W_a^B = W_{aa}^B \dot{a} + rW_a^B - \theta(P)\psi'(a). \tag{M1.78}$$

Then, at the balanced growth path, we know that $\lim_{t\to\infty} C = \infty$. and $\lim_{t\to\infty} P = \infty$, implying $\lim_{P\to\infty} = \theta(P) = \bar{\theta}$. Therefore, we write

$$u_c = W_a^B,$$

$$\rho W_a^B = W_{aa}^B \dot{a} + rW_a^B - \bar{\theta}\psi'(a).$$

This shows that the endogenous hazard problem reduces to our benchmark case presented in the main text with the constant probability of a catastrophe occurring. Of course, this is only valid for the balanced growth path, which is the focus of this study.

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