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CLIMATE CHANGE, CATASTROPHES AND THE MACROECONOMIC BENEFITS OF INSURANCE[1]

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ABSTRACT

This article considers the protective role that insurance can play in mitigating the negative macroeconomic and welfare impact of catastrophes, and the interplay between climate change and insurance coverage. The article first develops a theoretical model of insurance, climate change, catastrophes and the macroeconomy as a basis for the analysis. Predictions from this model are then empirically tested to explore how insurance has mitigated the impact of catastrophes in the past. Finally, we use these empirical results to explore the potential future impact of catastrophes using a range of climate-change related scenarios.

1. INTRODUCTION

There is little natural about natural catastrophes. The underlying peril is certainly natural, such as extremes of temperature, precipitation or wind, although even here the impact of humankind on climate is making an increasing contribution. Yet the impact of a catastrophe is ultimately determined by how exposed people and economic activity are to the peril, their vulnerability and which actions are taken beforehand and afterwards to mitigate the impact. Long-term drought in the middle of the Sahara has markedly less economic impact than lack of rainfall would in Saxony or Sardinia: little economic activity takes place there, and the inhabitants have adapted to the conditions.

Natural catastrophes, in short, are substantially man-made. Assessing their impact can only be effectively undertaken by considering exposure and mitigating actions taken to bolster resilience. This article considers one facet of that assessment: the protective role

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[1] This paper should not be reported as representing the views of the European Insurance and Occupational Pensions Authority (EIOPA) or of the European Central Bank. The views expressed are those of the authors and do not necessarily reflect those of EIOPA or of the European Central Bank.

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that insurance can play in mitigating the negative macroeconomic and welfare impact of catastrophes, and the interplay between climate change and insurance coverage.

Climate change is likely to bring about an increase in the frequency and magnitude of natural perils. Insurance can play an important role in helping to mitigate the impact of that greater risk, but at the same time insurance coverage may fall due to climate change. The future impact of catastrophes may consequently be greater than similar events in the past, and economic models which fail to account for this mechanism may underestimate the full magnitude of the costs of climate change.

We present here a new theoretical model that links insurance to macroeconomic performance in the short and long run, accounting for changes in the distribution of climatic conditions. The model provides three main conclusions: insurance can help mitigate the macroeconomic and welfare impact of catastrophes, climate change is likely to have an increasingly negative impact on welfare and that impact is likely to be magnified by a reduction in insurance coverage.

Those theoretical findings are supported by an empirical estimation of the macroeconomic impact of past natural catastrophes across developed and middle income countries, which demonstrates the beneficial role of insurance. A catastrophe causing 1% of GDP worth of damage is estimated to reduce GDP growth by around 0.2pp in the quarter of impact. However, if a high share of damages are covered by insurance, the initial fall in GDP may be averted. Projecting those estimates forward to the end of the present century using different global warming scenarios demonstrates that output losses from disasters could increase substantially, in particular should insurance coverage retreat from current levels. These findings further reinforce the necessity of meeting the Paris Agreement targets for limiting global warming.

To better understand how insurance can help mitigate the impact of catastrophes, it is useful to first consider how catastrophes affect the economy. When catastrophes strike, they damage capital, crops, livestock, lives and livelihoods. This destruction reduces both wealth and productive capacity. Dependent on the type of natural peril, there can be continued physical disruption – for example until floodwaters recede – as well as economic disruption through supply chains and damaged infrastructure that can far exceed the initial area of impact. Notable examples include the March 2011 earthquake and tsunami in Japan that affected automobile production nationwide (Matsuo, 2015), the 2018 drought in Germany where low river levels disrupted transport of oil and other commodities, and the current pandemic.

The initial phase of the disaster is usually followed by a period of rehabilitation as disruption wanes and eventually by reconstruction, which can take years to complete. In short, the overall economic impact of catastrophes extends beyond the initial direct damage (often described as "economic damage" in the insurance literature). The lost output in the months and years before full reconstruction, assuming it occurs, can far exceed the value of the initial direct damage.

Estimates of the welfare consequences of catastrophes have typically focused on GDP growth as a way of capturing both direct and indirect impacts (see, for example, Noy, 2009, Felbermayr & Gröshl, 2012, Fomby et al., 2013, Klomp & Valckx, 2014). But this is an imperfect measure, since it mostly captures changes to the flow of activity rather than changes to the stock of wealth. Moreover, reconstruction activity is recorded as positive in GDP numbers, while in reality it does not represent an increase in welfare relative to the counterfactual of no catastrophe since it diverts resources that could otherwise be used for productive investment, for improving the current housing stock, or for consumption (see Hallegatte and Przylkuski, 2010, for a more detailed description of estimating the costs of catastrophes).

Therefore, the aggregate welfare cost depends not just on the severity of the initial damage, but also on how swiftly reconstruction can be completed. Yet there is evidence that this phase can be prolonged and may even be incomplete in the absence of sufficient resources. Poverty traps can occur, where poorer households lack sufficient funds to cope with the disruption caused by catastrophes and end up in a permanently weaker financial situation (e.g. Carter et al., 2007, Nazrul Islam and Winkel, 2017). Broadly speaking, the paradox is that reconstruction requires funds, just at a time when economic activity, profitability and wealth may be depressed. The literature points to a substantial role for external financial support for activity and reconstruction – be it from international aid or domestic fiscal transfers – in reducing the overall impact of catastrophes (McDermott et al., 2014).

This is also why insurance can play a protective role. Insurance payouts can help households and businesses better endure the post-catastrophe disruption and underpin the reconstruction phase. Von Peter at al. (2012) find that the recovery from catastrophes is faster and more complete when the share of damages covered by insurance is higher. Indeed, aggregate GDP losses appear related to the uninsured component of damages rather than to the total amount. And firm-level evidence also demonstrates the protective value of insurance (Poontirakul et al., 2017).

While insurance has proven effective in some past episodes, coverage for catastrophes is patchy and there is currently a substantial protection gap. According to EIOPA estimates,[5] only 56% of damage caused by meteorological events (e.g. hurricanes and storm surges) in Europe is currently insured. For hydrological events (e.g. landslides and floods), the coverage falls to 28% and for climatological events (e.g. extreme temperatures, droughts and wildfires) just 7%. In a few countries, financial instruments other than private insurance are in place to mitigate the impact of disasters. For example, the Insurance Compensation Consortium in Spain is a public institution that covers losses arising from extraordinary risks, such as natural catastrophes and terroristic attacks, by charging an extra-premium on any private insurance contract. This mechanism provides insurance if damages are not covered by private policies. In France, a compensation scheme (CRR) in the form of a public-private partnership provides state-guaranteed unlimited reinsurance coverage against natural disasters and uninsurable risks.

Reducing the insurance protection gap could provide substantial welfare benefits and help reduce the social and economic impact of catastrophes. Closing the gap becomes even more important in the context of the expected increase in catastrophes brought about by climate change in the coming decades, an increase that will be particularly acute if the Paris Agreement targets are not met (IPCC, 2018). As reported by the International Association of Insurance Supervisors (IAIS) and Sustainable Insurance Forum (SIF), rising natural catastrophes are already resulting in increased claims, affecting the premiums and availability of non-life insurance, e.g. in property, transport and liability insurance.[6]

These developments also highlight how material climate change may widen the insurance protection gap. By affecting the frequency and correlation of events, climate change poses risks for insurance reserves and capitalisation and, ultimately, for insur-

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[5] Based on EIOPA pilot dashboard, MunichRe and SwissRe historical data (1980-2018 & 1970-2019). NatCatService data from MunichRe were taken from MunichRe's website in April 2020. Source links: https://www.munichre.com/en/solutions/for-industry-clients/natcatservice.html and https://www.sigma-explorer.com/

[6] See "Draft Application Paper on the Supervision of Climate-related Risks in the Insurance Sector", (October 2020).

ance supply. Under severe scenarios, it is possible that the insurance market for certain climate-related events becomes unviable if the willingness or ability of households and businesses to pay for insurance is lower than the premium for which insurers are willing to (or able to) accept the risk transfer. For example, recent devastating wildfires in California and Australia have resulted in widespread reports of difficulties with insurance renewal. A survey of Australian businesses last year found that more than half reported difficulties in obtaining insurance over the previous year, citing high growth in premiums, coverage being too limited, or not being available at all (Reed at al., 2020). And a study of major New Zealand cities found that even a small rise in sea levels could substantially increase flood risk and that at least partial insurance retreat was likely within the coming decade (Storey et al., 2020).

The following sections present in turn a theoretical model of insurance, climate and the macroeconomy, empirical evidence of how insurance has in the past mitigated the impact of catastrophes, and an illustration of the potential future impact of catastrophes using different of global warming scenarios.

2. A THEORETICAL MODEL OF THE MACROECONOMIC IMPACT OF CLIMATE CHANGE AND INSURANCE

The environmental economics literature provides extensive evidence that climate change affects the level of output and the economy's ability to grow in the long-term. In this section, we model the role of insurance in mitigating the macroeconomic costs of climate change by distinguishing the long-term effect of gradual but persistent changes in climate variables, such as temperature and precipitation (chronic physical risks), from the short-term effect of more frequent and severe extreme weather events, such as floods, storms, droughts and wildfires (acute physical risks).

We show that insurance is beneficial to the economy, as it mitigates losses when disasters occur and reduces the recovery period by facilitating investment. But changes in climate variables as well as more frequent and severe natural catastrophes may reduce the supply of insurance and increase its costs. In particular, the model shows that the macroeconomic and welfare costs of climate change are likely to be greater than they would otherwise be because of this potentially growing insurance protection gap. We start with a baseline growth model that incorporates disaster risk in the presence of insurance but abstracts from climate change (section 2.1). Then we turn to the impact of climate change via a gradual increase in temperatures and more frequent natural hazards that affect the insurance market (section 2.2).

2.1 MODELLING OUTPUT IN THE FACE OF NATURAL DISASTERS

Consider an economy in which aggregate production is described by the following production function, where L and K are labour and capital inputs, and Λ is labour productivity:

$$Y_t = F(\Lambda_t L_t, K_t) \tag{1}$$

We start by focusing on modelling the impact of natural disasters on output growth through capital, in the presence of insurance. The model assumes diminishing returns on capital, such that $dY / dK > 0$,and $d2Y / dK < 0$. When disasters occur, total capital is reduced. We map changes in capital to three variables: the total amount of capital in the absence of disasters K, the amount of damaged capital upon a disaster K_d and the insurance payout K_i as shown in Equation (2). In the absence of disasters, output is given by the long-term production function in Equation (1). Output growth is constrained following a disaster because both the available capital stock decreases, and because resources are reallocated away from the optimum (see also Hallegatte and Vogt-Schilb, 2019):

$$Y_t = \left(1 - \left(\frac{K_d - K_i}{K}\right)\right) F(\Lambda \mathrm{L}, K) \tag{2}$$

We assume that assets that were not directly damaged by the disaster continue producing with an unchanged productivity, although in reality their productivity could be reduced due to indirect effects.

The impact of natural disasters and insurance on capital and economic growth

We assume that disasters occur as discrete downward jumps to the capital stock and can be modelled as Poisson arrivals with a mean arrival rate π. Here we assume this probability to be fixed, at least in the short-term, but in section 2.2 we will allow π to vary as a function of climate change. K_d denotes the amount of damaged capital, $K_d = (1 - Z)K$, where Z is the undamaged share of capital. For simplicity, we assume that the loss given event is independent of risk adaptation, i.e. households and firms cannot reduce the damage.[7] $K_i = WK_d$ is the insurance payout in the event of a disaster and is equal to the total amount of insured capital that is damaged, where W indicates the share of damaged capital covered by the insurance. The insurance payout K_i cannot be larger than the damaged capital K_d, therefore $W \leq 1$. Abstracting from labour, output can be written as:

$$Y = F(K, K_d, K_i) = K - K_d + K_i = K - (1 - W)(1 - Z)K \tag{3}$$

where $(1 - W)(1 - Z)K$ is the uninsured damage. This expression defines the insurance protection gap. The protection gap increases as either Z falls for a given level of W (e.g. a bigger disaster that affects a larger share of capital), or as W decreases for a given level of Z (a smaller share of capital is insured). If there is no disaster, i.e. $K_d = 0$ and $Z = 1$, changes in output depend only on changes in capital. In the presence of full insurance, i.e. $K_i = K_d$ and $W = 1$, changes in output also depend on capital only, independently from damages. In the complete absence of insurance activity, i.e. $W = 0$, changes in output depend on changes in capital and the severity of damages, $Y = ZK$, for a given level of disaster probability π.

In each period, aggregate output can be spent on consumption C, investment I and insurance premiums P. These insurance premiums determine the degree of insurance coverage which, as modelled in Equation (3), reduces damages upon a catastrophe event by shortening the recovery period. We do not distinguish here between public and private investments and we abstract from other mitigation spending that may reduce the damage from disasters, e.g. seawalls or land-use zoning (Hong et al., 2020). The uninsured damages at time t depend on pre-disaster insurance spending. Investments are adjusted by a cost function $\Phi(I,K)$ that captures effects of depreciation and costs of installing capital (Pindyck and Wang, 2013). In the presence of adjustment costs, the capital is not perfectly liquid and cannot be used for consumption without incurring some costs, i.e. consumption and investment are not perfectly substitutable.

$$Y = C + (I + \Phi) + P \tag{4}$$

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[7] Alternatively, the loss could be modelled as a function of adaptation as in Fried (2020), $K_d = (1\text{-}Z)KF(a)$, where a denotes the adaptation capacity.

$$\Phi(I,K) = \phi(i)K \tag{5}$$

where i is the investment-capital ratio, $i = I/K$,and $\varphi(i)$is increasing and concave. After a disaster, damaged assets are replaced or repaired by reducing consumption and regular investment. Following Hallegatte et al. (2007), we define two types of investments: investment towards reconstruction of the damaged capital, I_R, that increases the residual capital remaining after disasters, and investment into new capital, I_N, that would regularly increase the production capacity K (i.e. independent of disasters). The marginal return on reconstruction is higher than the marginal return on new capital, consistent with empirical evidence: e.g. following disasters, the construction of new buildings and infrastructure would be postponed to rebuild the damaged ones. Therefore, when capital is destroyed in a catastrophe, investment is first devoted to replacing the destroyed capital.

The time it takes to rebuild destroyed capital depends not only on the extent of the losses, but also on the cost and availability of financial tools for households and firms (Hallegatte et al., 2007). In practice, the pace of reconstruction, I_R, can be limited by a lack of savings or borrowing capacity, for example, or by limited production capacity in certain sectors, such as construction. This leads to consumption losses since C would be reduced in favor of I and reconstruction periods would be much longer than what the initial amount of damage would suggest. Insurance can relax these financial constraints by quickly repaying insured damages and reducing consumption losses. At the same time, I_R is bounded by the amount of total investment that can be mobilized. We assume that all investment is devoted to reconstruction because of the higher return of I_R with respect to I_N, and that output losses are reduced to zero exponentially with a characteristic time of reconstruction R. This implies that the economy returns to its pre-disaster state, although in practice some activities could be permanently destroyed. Output losses after t_0 are then given by:

$$\Delta Y = \mu \Delta K e^{-\frac{t-t_0}{R}} \tag{6}$$

where μ is the average productivity of capital $F(L, K)/K$. The duration of the reconstruction phase therefore determines the macroeconomic cost of natural disasters. If damages can be repaired immediately, output losses will be zero, but consumption will be reduced to reconstruct (i.e. $\Delta C = \Delta K$). By contrast, if there is no reconstruction, output losses will be permanent ($R = \infty$) and will be absorbed by consumption (i.e. $\Delta C = \Delta Y = \mu \Delta K$). Assuming that the productivity of destroyed capital is equal to the average pre-disaster productivity of capital, the model therefore implies that the net present value of consumption losses is larger than direct losses when reconstruction takes some time, as $\mu \Delta K > \Delta K$.In other words, consumption and welfare losses are magnified when reconstruction is delayed or slowed down.

We can also translate the model to determine what it implies for the economy's growth rate by augmenting a standard specification of capital stock evolution in the presence of disasters (Barro, 2006; Pindyck and Wang, 2013; Hong et al., 2020) to incorporate the effects of insurance. The capital stock is subject to stochastic fluctuations and jumps, and evolves as follows:

$$dK_t = \Phi(I_{t-1}, K_{t-1})dt + \sigma K_{t-1} dB_t - (1-W)(1-Z)K_{t-1} d\mathcal{J}_t \tag{7}$$

The first term is investment, adjusted for depreciation and costs of installing capital, as defined in equation (5) (Pindyck and Wang, 2013). The second term captures continuous shocks to capital that are standard in macroeconomic models, where B_t is a standard Brownian motion and the parameter σ is the diffusion volatility of the capital stock growth. $t-1$ denotes the pre-jump time. The third term represents the effect of disasters.

J_t is a jump process reflecting the probability of a natural catastrophe with a fixed but unknown arrival rate, π. When the jump arrives, it destroys K_d, which is a fraction $(1 - Z)$ of capital K. The novelty of our model is that in the presence of insurance, this fraction is reduced by (1-W) times, as also shown in equation (3). If the catastrophe does not arrive, the third term is zero. The higher the arrival rate π, for example due to climate change, the more likely that the capital stock will be hit by a disaster. Substituting the expression for depreciation and installation costs (5) into (7) and taking the first derivative of capital stock K_t, we can see that:

$$dK_t/K_t = \phi(i^*)dt + \sigma dB_t - (1-W)(1-Z)d\mathcal{J}_t \tag{8}$$

where i^* is the optimal investment-capital ratio, constant in equilibrium. The expected growth rate, denoted by $\bar{g}$, is then

$$\bar{g} = \phi(i^*)dt - \pi E(1-W)(1-Z) \tag{9}$$

where the second term is the expected percentage decline of the capital stock due to catastrophes. While insurance may crowd out investment, it enhances long-run growth by reducing the expected loss due to catastrophes, $E(1 - W)(1 - Z)$.

Insurance premiums p_{t-1} mitigate the effect of disasters by insuring a share W of damages, so that the remaining share of capital after disaster conditional on the event arrival at time t, i.e. $(1 - W)(1 - Z) = Z + W(1 - Z)$, depends on pre-disaster insurance spending P_{t-1}:

$$W_t(1-Z_t) = p_{t-1} \tag{10}$$

where $W_t(1 - Z_t)$ is the share of insured damages and p_{t-1} is the pre-disaster unit cost of insurance. If insurance spending P_t increases, then the benefit increases as well, but less than proportionally, i.e. insurance has decreasing returns to scale. In the next section, we therefore consider the determinants of insurance cost.

The cost of insurance

For a given probability of an adverse event, π, insurance is beneficial in expectation, with the benefits deriving from the reduction of (uninsured) damage after disasters. The price of insurance claims is modelled as follows:

$$p(W,Z) = \alpha\pi(1-Z)W \tag{11}$$

where α reflects the insurance risk premium and depends on the risk aversion of insurance capital providers, $\pi(1 - Z)$ is the expected damage of a disaster and $\pi(1 - Z)W$ is the amount of damage insured. If the policyholder insures the whole capital at risk, $p(W,Z) = p(Z)$. Should the shock arrive, the policyholder would receive a lump-sum payoff of one unit of consumption. If the disaster probability (arrival rate) π increases, the insurance premium would increase too, as insurers will pay more claims. At the same time, for a given Z, the insured share W would decrease. This allows us to model the insurance cost endogenously. Lane and Mahul (2008) show empirically that the price of a catastrophe bond can be modelled as a multiple of expected loss, as in equation (11).

The risk charge reflects the cumulative feature of disaster risks that affect many policyholders at the same time. The higher is α and the bigger the loss, the higher the insurance premium, as the ability of insurers to diversify their portfolio and pool risks together decreases. Carayannopoulos et al (2020) and Dieckmann (2010) suggest that risk aversion among insurance capital providers can increase the value the insurance risk premium

α, for example after major natural disasters. For simplicity, we abstract here from the distinction between insurance and reinsurance providers.

We assume that if the probability of a catastrophe, π, increases, the demand for insurance K_i will also increase as the benefit of insurance will be larger other things being equal. But insurance supply is limited to a quantity, M, $K_i \leq M$, which depends on insurers' risk aversion. If the buyer of insurance knows the capital at risk and is strictly risk averse, then he will completely insure against the event, i.e. $W = 1$. In this model, we assume that the buyer cannot influence the probability or severity of a natural event. Otherwise, the insurer will offer only partial insurance, $W < 1$, so that the buyer has incentives to reduce risk/losses. If the policyholder could influence the probability or severity of disasters in our model, then the level of insurance would depend on such adaptation capacity, because a consumer with high adaptation capacity suffers lower damage and therefore chooses to insure less, i.e. lower W.

The insurance protection gap can widen for several reasons that relate both to insurance supply and demand. Insurers' risk aversion typically increases after large natural disasters. Also, a lack of awareness or willingness to buy insurance cover even when it is affordable and accessible, is not uncommon in many developed countries.[8] But the protection gap may also widen from the rising price or the unavailability of certain types of insurance coverage, especially due to risk factors related to climate change. If the frequency or severity of disasters rises globally, this may increase the insurance risk premium and reduce its risk pooling benefit. In this situation, buyers are aware and willing to buy insurance cover but are unable to do so due to unaffordability or insufficient availability.

2.2 INCORPORATING THE IMPACT OF GRADUAL CHANGES IN CLIMATE VARIABLES ON CAPITAL

Thus far, we have abstracted from the impact of climate change in the model. Climate change can affect output both via a gradual change in climate-related variables and more frequent natural hazards. In the next step, we consider only the direct effects of gradual global warming on capital, that affect neither the probability nor the severity of an adverse natural event and that cannot therefore be mitigated by insurance. In the final section, we introduce the impact of more frequent disasters on insurance activity, i.e. on the insurance protection gap, and therefore on output.

We start by modelling the impact of gradual changes in climate-related variables, such as temperature, T, and precipitation, on capital by exploiting the approach of Kahn et al. (2019). In particular, we consider the deviations from the historical norms of climate variables. In contrast to Kahn et al. (2019), we focus here on the impact of global warming (i.e. changes in T) on output growth, via gradual losses of physical capital related, for example, to land desertification or sea level rise, and we abstract from the impact on labour productivity. Gradual warming could also reduce the productivity and availability of natural resources as well as negatively affect certain aspects of the capital stock. For example, some machinery and equipment may not be able to operate as effectively above certain temperatures, or higher temperatures may accelerate the rate of depreciation of the capital stock. We abstract here from the development of new technologies that could mitigate these effects over time.

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[8] Aon Benfield's "Reinsurance Market Outlook," published in July 2019, said, "*Even in developed countries with the most mature insurance markets in place, there are several perils and sub-perils of events that remain highly uninsured.*"

The historical norms are regarded as capital neutral, in the sense that if climate variables remain close to their historical norms, they are not expected to have any gradual long-term effects on capital. In this step, we also assume that K_d and K_i are not affected by gradual changes in climate-related variables.

Specifically, we consider the following specification for changes in capital due to temperature:

$$K(x_t) = K_t \omega_0 \exp\,(-\omega x_t) \tag{12}$$

where $x_t = (T - T^*_{t-1})$, ω_0 is a positive constant and the exponential function is a multiplicative shifter of capital, with ω being the sensitivity of physical capital to climate change, and also assumed to be positive, so that climate change adversely affects the capital stock. The historical norms (i.e. T^*) are assumed to be fixed to reflect current temperature patterns. By substituting equation (12) into (3), we obtain the following:

$$Y_t = F(K_t, K_{dt}, K_{it}, x_t) = K_t \omega_0 \exp(-\omega x_t)\,[1 - (1 - W)(1 - Z)] \tag{13}$$

Equation (13) shows that if there is no deviation of temperatures from historical norms (so that $x_t = 0$), output would be the same as in equation (3). But if changes in temperature directly affect capital, without changing the probability of a disaster, then the output in equation (13) is smaller than in equation (3) substituting $exp(-\omega x_t) < 1$. In short, regardless of the provision of insurance, output and welfare are likely to be lower in the presence of climate change.

The impact of changes in climate variables on capital through disaster insurance

Global warming is also likely to affect output by making adverse natural events more frequent or more severe. This affects output *directly* by increasing losses from disasters, and *indirectly* via the widening protection gap. The direct effect can occur even if the protection gap doesn't widen. In this section, we focus on the indirect effect of an increase in disaster probability, π, on insurance coverage. As an alternative, we could also consider the effect of an increase in severity, Z. As shown in equation (11), insurance premiums would increase as a consequence of increased disaster risk and insurance coverage would decline, a process called insurance retreat in the literature. Alternatively, insurers could introduce terms in insurance policies that transfer part of the risk to the policy holder (partial retreat) (Storey et al., 2020).

We modify equation (11) to account for changes in insurance premiums due to climate variables:

$$P(W, Z, x) = \alpha\pi(1 - Z)W \exp(\psi x_t) \tag{14}$$

where ψ is the sensitivity of disaster probability to climate change. If there is no deviation of climate variables from historical norms ($x = 0$), insurance on physical capital will depend on the insurance risk premium and expected damages as in equation (11), and the output model collapses to equation (3). If climate change increases insurance costs, a positive ψ would be associated with higher premiums and therefore lower insurance coverage, i.e. a higher protection gap.

$$Y_t = F(K_t, K_{dt}, K_{it}, x_t) = K_t \omega_0 \exp(-\omega x_t)\,[1 - \left(1 - W exp(-\psi x_t)\right)(1 - Z)] \tag{15}$$

Given the inverse relationship between insurance cost and coverage, the sensitivity of the disaster probability enters the expression with a negative sign. As above, the historical norms are regarded as insurance neutral, in the sense that if climate variables remain close to their historical norms, they are not expected to have any effects on the probability of the adverse natural event and therefore on insurance. If insurance coverage is negatively affected by climate change, the output in equation (13) is larger than in equation (14) because $exp(-\psi x_t) < 1$ if $\psi > 0$. If there is no insurance, equations (13) and (15) are equivalent.

Overall, the theoretical model presented here provides several important conclusions. First, disasters are costly and influence output through their increasing frequency. Insurance can help mitigate the impact of disasters by relaxing financial constraints and accelerating the rebuild, thereby reducing the overall welfare loss. Second, the gradual increase in temperatures above historic norms can result in lower productivity and lower output overall, for which insurance can offer little protection. Finally, an increase in the probability of natural hazards can result in a widening of the insurance protection gap, which exacerbates the detrimental effect of increasing climate-related catastrophes on capital, output, growth and welfare.

3. EMPIRICAL EVIDENCE OF THE IMPACT OF THE PROTECTION GAP

In this section, we empirically test some of the predictions from the theoretical model, specifically the growth equation (9). Abstracting from the stochastic properties of that equation, it implies that the growth rate of an economy is adversely affected by damage from natural disasters, but insurance can play a role in mitigating their impact. More formally, for a given period *t*, Equation (9) can be rewritten as:

$$(14) \qquad g_t = \phi_t - \mathrm{E}\,(1 - W_t)(1 - Z_t) = \phi_t - \mathrm{E}\,(1 - Z_t) + \mathrm{E}\,W_t(1 - Z_t)$$

where Φ_t is a growth rate in period *t* without any disaster damage (i.e. when $Z_t = 1$), $(1 - Z_t)$is the share of capital damaged by a disaster (or a set of disasters) occurring in period t, W_t is the share of the damaged capital covered by insurance and E is a non-linear function. Using Taylor's theorem, we obtain the linear approximation of this function from the first order Taylor polynomial and approximate the growth rate of a country *c* in period *t* as follows:

$$(15) \qquad g_{ct} = \phi_{c,t} + \beta_1 * \left(1 - Z_{c,t}\right) + \beta_2 * W_{c,t} * \left(1 - Z_{c,t}\right)$$

Furthermore, decomposing $\Phi_{c,t}$ into a country fixed effect α_c, a time fixed effect ϑ_t and a random error term $\varepsilon_{c,t}$, we derive the following empirical specification:

$$(16) \qquad g_{ct} = \beta_1 * \left(1 - Z_{c,t}\right) + \beta_2 * W_{c,t} * \left(1 - Z_{c,t}\right) + \alpha_c + \theta_t + \varepsilon_{c,t},$$

In line with our model, we expect $\beta_1 < 0$ and $\beta_2 > 0$.

To account for the non-linearities in the theoretical model, we also derive a complementary empirical specification from equation (16) by transforming the continuous variables $(1 - Z_{c,t})$ and $W_{c,t}$ into dummy variables to distinguish between large-scale natural disasters with low and high shares of insured losses. The coefficient for large-scale natural disasters with a low share of insured losses is then expected to be negative (as in the case of β_1) and the coefficient for large-scale natural disasters with a high share of insured losses is expected to be higher than this (derived from $\beta_1 + \beta_2$).

DATA

For the dependent variable, we use quarterly data on real GDP growth rates from the OECD, which are available for a sample of 45 countries, including 8 non-OECD countries. This naturally skews the sample towards more developed economies. The sample does also include some emerging market economies (including Brazil, India, Russia, South Africa and Turkey), but no country classified as low income by the World Bank is present. By focusing on GDP growth rates, our empirical analysis follows the theoretical model and the approach of most other studies in this field (e.g., Noy, 2009, Felbermayr & Gröshl, 2012, Fomby et al., 2013, Klomp & Valckx, 2014). Yet GDP growth is only an imperfect proxy for capturing the overall welfare consequences of catastrophes, since it captures changes to the *flow* of activity rather than changes to the *stock* of wealth.

To proxy the share of capital damaged by natural disasters and the share of damaged capital covered by insurance, we use EMDAT, an international disasters database collected by Centre for Research on the Epidemiology of Disasters.[9] The EMDAT database contains information about individual disaster events across the globe since 1980. Owing to a somewhat lower coverage in early years, we only use data since 1996 and focus on four types of natural disasters: climatological (411 events), geophysical (521 events), hydrological (2,275 events) and meteorological (1,995 events).[10] The most common events are floods (38% of all events) and storms (31%). A typical drought (climatological disaster) results in the largest damages (median around $860mn), followed by an extreme temperature event (median ~ $300mn), a storm (median ~$170mn) and a wildfire (median ~ $140mn). While earthquakes display a relatively limited median damage (around $90mn), the distribution is highly skewed to the right by events with exceptionally large damages, resulting in the largest mean among all types of events (around $2600 mn).[11] Although geophysical disasters such as earthquakes are independent of climate change, we include them in our analysis to increase the sample size, especially in relation to very large disasters.

While the database includes over 5,000 disaster events across the globe for the period of our analysis, information on financial damages is only available for about 2,300 disasters. Within those, a split between insured and uninsured losses is available only for around 650 events (see Table 1), with both the mean and median share of insured losses being around 40%. But those disasters with the split are in general much larger, which are likely to be more relevant in terms of macroeconomic impact. In particular, the average financial damage for disasters where insured losses are available is $3.2 billion, almost ten times higher than the average damage of disasters where the split between insured and uninsured damages is unavailable.

However, to increase the number of events for our empirical analysis, we impute insured and uninsured losses for most events where data on total damages are available. The values are imputed based on a country-specific regression models, where the dependent variable is the share of insured losses in total damages and the explanatory variables include the log of total damage and dummies for eight different types of disaster (drought, earthquake, extreme temperature, flood, landslide, mass movement, storms, volcanic activity, wildfire) to the extent applicable for a given country. For some countries, the model cannot

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[9] Available under www.emdat.be.

[10] These are the disaster types most studied in the literature. Excluded types include technological disasters, which are typically factory and transport accidents and therefore generally small and localised, biological disasters, which in general have smaller initial impact on capital (although as the current pandemic shows there can be substantial indirect impacts) and extra-terrestrial (a meteor strike in Russia).

[11] All values are in this paragraph are in constant 2010 USD.

be estimated owing to a low number of observations, resulting in around 250 events with damage data but no imputed values for insured/uninsured losses. In the empirical exercises below, we present results based on both the smaller sample where insured and uninsured losses are split in the data and the wider sample which exploits the imputed split.

Table 1: Results of data imputation for insured and uninsured losses (values in constant 2010 $)

	Damages	Insured	Uninsured	# events
Original dataset				
Information on (un)insured losses	\$2.1 trillion	\$0.7 trillion	\$1.4 trillion	657
Information on total damage only	\$0.6 trillion	-	-	1,654
No information on damage	-	-	-	2,891
Total				5,202
Dataset with imputed values				
Information on (un)insured losses	\$2.7 trillion	\$0.9 trillion	\$1.8 trillion	2,066
Information on total damage only	<\$0.1 trillion			245

Sources: EMDAT and authors' calculations.

We proxy the share of capital damaged by disasters in country c and quarter t by the share of financial damages from (all) disasters in that quarter and country relative to country GDP lagged by one year. We obtain the GDP level data from the World Development Indicators (WDI) and use constant 2010 USD for the calculation. The mean (median) disaster cost is 0.25% (0.029%) of GDP in the full EMDAT sample, which declines to 0.16% (0.027%) of GDP for our sample of countries where quarterly GDP data are available. The lower mean impact reflects the fact that quarterly GDP data are mainly available for developed countries, where natural disasters have typically had a smaller impact relative to GDP in the past. In this smaller sample, the disaster damage exceeds 1% of GDP for only 18 observations. The share of the damaged capital covered by insurance $(1 - Z_{c,t})$ is then proxied as the share of insured financial losses in total disaster damages. The share of insured losses is somewhat higher in the sample with quarterly GDP data (median at 47%) as compared to the world-wide EMDAT sample (median at 40%).

EMPIRICAL RESULTS

Using a panel regression with standard errors clustered by country, we estimate equation (16) and report the results in Table 2. We start by focusing in column (1) on the sample for which insured and uninsured losses are split in the underlying dataset. The sign of the coefficients is as expected, with greater damages from disasters being associated with a lower growth rate but with this effect being mitigated by a higher share of insured losses. The statistical significance of both coefficients improves when we use the larger sample with imputed data in column (2), while the size of the coefficients remains almost unchanged.

These estimated coefficients suggest that if a large disaster of 1% of GDP hits a country, the quarterly GDP growth rate declines by 0.25 percentage points in case of no insurance coverage (e.g. from the median of 0.7% in our sample to 0.45%; see the left panel of Figure 1). However, if 25% of the losses are insured, the GDP growth rate is estimated to only decline by around 0.15 percentage points. The effect is even smaller, around 0.06 percentage points, if half of the losses are insured. For unusually high shares of insured losses – e.g. a 75% insured share corresponding to the 90th percentile of the distribution – our empirical model even suggests an almost immediate (within quarter) rebound in GDP growth.

Table 2: Regression results – panel estimates

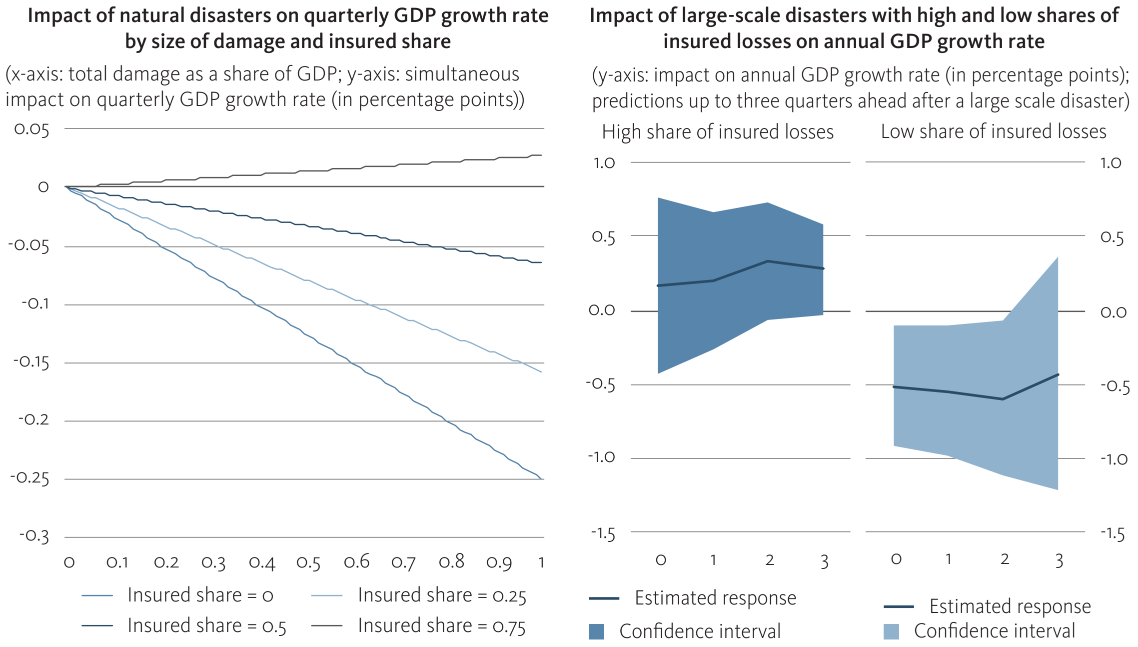
Dependent variable	**quarterly GDP growth rate (in %)**			
	(1)	**(2)**	**(3)**	**(4)**
Sample	**Original**	**Imputed**	**Original**	**Imputed**
Damage as a share of GDP (%)	-0.25*	-0.24**	-0.26*	-0.25*
	(0.07)	(0.05)	(0.07)	(0.06)
--> lag 1			0.28***	0.0040**
			(0.00)	(0.04)
Damage as a share of GDP (%) * Share of insured losses (%)	0.0037*	0.0037**	0.0042**	0.19**
	(0.05)	(0.03)	(0.05)	(0.05)
--> lag 1			-0.0043***	-0.0025
			(0.00)	(0.13)
Country fixed effects	Y	Y	Y	Y
Time fixed effects	Y	Y	Y	Y
Observations	2,938	3,431	2,214	2,827
R-squared	0.203	0.188	0.224	0.206
Number of countries	45	45	45	45

Notes: Panel regression using standard errors clustered by country. *, **, *** denote significance at 10, 5 and 1% confidence level. P-values are reported in parentheses.

To further investigate such potential rebound effects, we test the effect of lagged disaster damage and insurance coverage on the quarterly GDP growth rate in columns (3) to (4). The results suggest that, on average, there is a rebound in GDP growth one quarter after a disaster happens (coefficients of further lags are estimated as insignificant). However, while reconstruction activity is recorded as positive in GDP growth numbers, in reality it does not represent a gain to welfare since it takes away available output that could otherwise be used for improving the current capital stock, or for consumption (see Hallegatte and Przylkuski, 2010, for a more detailed description of estimating the costs of catastrophes).

To account for the non-linearities in the theoretical model, we estimate an alternative empirical specification using two dummy variables to capture large-scale natural disasters with high and low shares of insured losses respectively. In view of the relatively high volatility of quarterly GDP data, we use as the dependent variable the annual GDP growth rate in each quarter (calculated as the year-on-year difference in the log of GDP) and include several lags of the two dummy variables. The results presented in the right panel of Figure 1 confirm the adverse effect on the GDP growth rate from large-scale natural disasters when insurance coverage is low. This adverse effect is then estimated to drag on the annual GDP growth rate for up to three quarters after the disaster.[12] For large-scale disasters with a high share of insured losses, the GDP growth rate is – in line with the theory – estimated to be higher and does not deviate significantly from its long-term trend. This suggests that insurance supports GDP growth after disasters, likely as insurance payouts can support reconstruction.

Figure 1: The impact of natural disasters on quarterly GDP growth rate by size of damage and insured share


Impact of natural disasters on quarterly GDP growth rate by size of damage and insured share

(x-axis: total damage as a share of GDP; y-axis: simultaneous impact on quarterly GDP growth rate (in percentage points))

Impact of large-scale disasters with high and low shares of insured losses on annual GDP growth rate

(y-axis: impact on annual GDP growth rate (in percentage points); predictions up to three quarters ahead after a large scale disaster)

Notes: Left panel: Based on estimates in column (1) of Table 2. Right panel: The charts show the impact of large-scale natural disasters (with total damage larger than 0.1% of GDP) when the share of insured losses is high (above 35%) and low (below 35%). The estimates are obtained using a panel regression model with standard errors clustered by country and the sample with imputed data. For the quarter including the date(s) of the disaster (t=0) and the three subsequent quarters, the y-axis measures the percentage point impact of the disaster on the year-on-year annual growth rate at the end of that quarter.

4. THE POTENTIAL IMPACT OF DIFFERENT CLIMATE CHANGE AND PROTECTION GAP SCENARIOS ON THE MACROECONOMY IN A EUROPEAN CONTEXT

In this section, we link the findings of the theoretical model and empirical results to the possible evolution of key climate-change related perils under different warming scenarios.

The analysis starts by taking various Representative Concentration Pathways (RCP) developed by the Intergovernmental Panel on Climate Change to give different global warming scenarios. Assuming that no adaptation or mitigation measures will be introduced to limit the impact of climate change, the potential future financial damages due to natural disasters in a European context are then mapped on to GDP, under different protection gaps and warming scenarios, using the empirical results from the previous section.

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[12] This is consistent with the rebound in the quarterly GDP growth rate estimated in Table 2.

The RCP pathways underpin the analysis carried out in the PESETA IV report, which calculates for Europe, including the UK, estimated annual damages and GDP losses arising from climate-related catastrophes, based on granular regional and sectoral models and assuming no adaptation or mitigation measures. Table 3 presents the expected annual damages for key perils[13], while Table 4 shows the expected annual damages as share of GDP without damage reduction measures.

Table 3: Expected annual damages from climate-related catastrophes without adaptation and mitigation measures (in million €)

EU and UK (2015 values)	**Baseline (1981-2010)**	**2050**		**2100**		
		1.5°C	**2°C**	**1.5°C**	**2°C**	**3°C**
Windstorm	4,594	6,829	6,913	11,260	11,393	11,422
Droughts	9,048	12,354	15,475	24,723	31,457	45,380
River flood	7,809	15,609	21,268	24,072	33,081	47,824
Costal flood	1,400	10,900	14,100	*10,900*	110,600	239,400
Total	22,851	45,692	57,756	70,955	186,531	344,026

Source: JRC PESETA IV report. Note: The 1.5 degree figure for costal flood was not included in the source and is estimated for the purposes of this article. The Peseta IV report focuses on the 1.5°C and 2°C warming levels in 2050 as 3°C warming by mid-century is not considered a realistic scenario.

We combine the PESETA IV damage estimates with data from EIOPA's ongoing work on the insurance protection gap dashboard[14] to generate six scenarios. We take two potential warming paths – RCP4.5 (labelled here as moderate) and RCP8.5 (labelled here as severe) and their associated expected annual damages from Table 3. For each of these paths we consider three potential degrees of insurance coverage: current, which corresponds to the share of losses that are covered today (insured share of 30%), zero insurance coverage and full coverage.

We aggregate, across all the considered perils and European countries, the PESETA IV estimates on expected annual damages as share of the projected GDP based on the future socioeconomic conditions set out in the Commission's ECFIN 2015 Ageing report[15]. The expected future damages as share of the projected GDP are summarised in Table 4. Expected annual damages are estimated to increase from the baseline of 0.17% of GDP to 0.21% in 2050 under the moderate scenario and 0.29% in the severe scenario. By 2100 these losses are projected to increase to 0.41% and 0.76% respectively. In other words, expected annual GDP losses from natural perils are projected to increase by between 2.5 and 4.5 times by the end of the current century. Looking at the expected annual damages by mid- and end-century under the same warming scenario, the EAD as share of GDP may seem lower in 2100 than in 2050, but this can be explained by the fact that these figures are linked to different RCP pathways. For example, under the "moderate" warming scenario the mean global temperature is expected to increase by approximately 1.5°C by 2050, however under the same pathway the temperature would increase by almost 2°C

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[13] These estimates include the annual GDP loss in the EU, including the UK, arising from climate-related catastrophes, based on granular regional and sectoral models. The perils were selected on the basis on data availability and comparability with the modelling framework. The full results of PESETA IV can be found at https://ec.europa.eu/jrc/en/peseta-iv.

[14] For further information please see: https://www.eiopa.europa.eu/content/pilot-dashboard-insurance-protection-gap-natural-catastrophes_en

[15] The 2015 COM Ageing Report: Economic and budgetary projections for the 28 EU Member States (2013-2060): https://ec.europa.eu/economy_finance/publications/european_economy/2015/pdf/ee3_en.pdf

by 2100. In other words, the expected results under the 2050 (1.5°C) should be compared with the foreseen results in 2100 in a 2°C warming scenario.

Table 4: Expected future annual damages from climate-related catastrophes as a share of GDP without adaptation and mitigation measures

EU and UK (2015 values)	Baseline (1981-2010)	2050		2100		
		1.5°C Moderate	2°C Severe	1.5°C	2°C Moderate	3°C Severe
Total (windstorm, droughts, river and coastal flood)	0.17%	0.21%	0.29%	0.19%	0.41%	0.76%

Source: JRC PESETA IV Report and authors' calculations.

Finally, we exploit the empirical estimates presented in Section 3 (Table 2, column 2) to give an indicative comparison of the evolution of GDP under the six scenarios (Figures 2a and 2b). Naturally, the uncertainty around estimates 30-80 years into the future is substantial due to material uncertainties in the climate and economic projections. In particular, these results assume that no action would be taken to counteract the increasing risk related to climate change through mitigation or adaptation measures. In this context, the results show that under both the RCP4.5 and RCP8.5 paths, differences in insurance coverage could have economically material effects on GDP. The difference between the GDP level assuming full and no insurance is around 2% under RCP4.5 and around 3% under RCP8.5 in 2050. By the end of this century, the difference widens to around 8% and 14% respectively.

Figure 2.a.

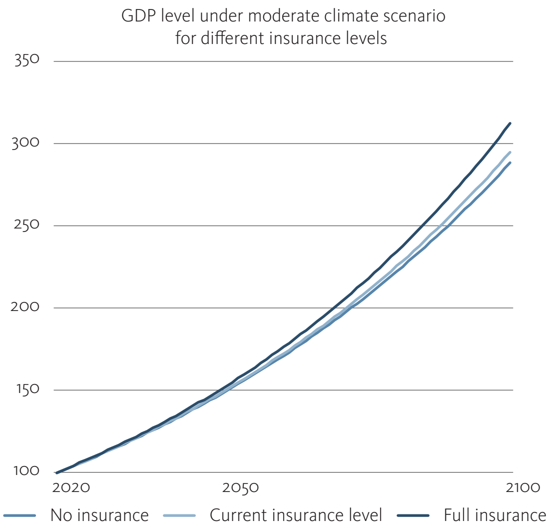
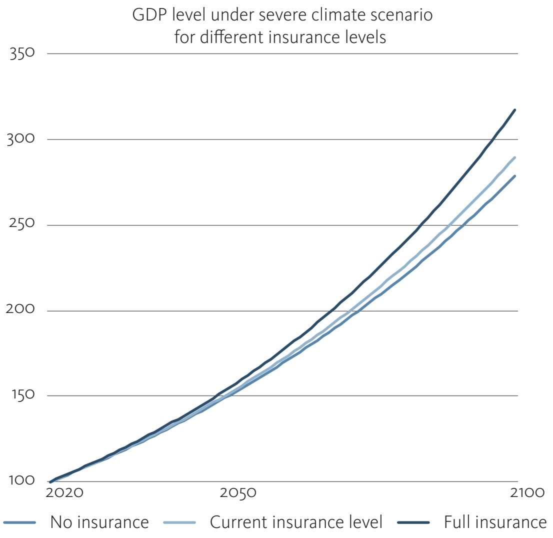


Figure 2.b.



Source: PESETA and authors' calculation.
Notes: The moderate (left panel) and severe (right panel) scenarios correspond to an increase in temperature by 2 and 3 degrees by 2100, respectively, and reflect two Representative Concentration Pathways (RCP) developed by the Intergovernmental Panel on Climate Change (IPCC). The GDP level is indexed to 100 in 2020. The annual GDP growth rate without damages from climate-related catastrophes is assumed to equal 1.4% (similarly as in The 2021 Ageing Report). The estimated annual damages from climate-related catastrophes in Europe are based on PESETA IV report, which estimates these damages for different RCP pathways using granular regional and sectoral models. No adaptation or mitigation measures are considered. The estimated impact of these damages on the GDP growth rate with different shares of insured losses is based on estimates in column (1) of Table 2.

5. CONCLUSION

Climate change, even under moderate scenarios, is likely to bring about a marked increase in natural perils both in Europe and globally. The theoretical and empirical results presented in this feature demonstrate that the aggregate welfare impact of that increase is not pre-determined. Setting aside the actions that can be taken to transition to a carbon neutral economy and thereby limit the extent of warming, insurance has a key role to play in mitigating the impact of future catastrophes. By accelerating reconstruction and limiting the period of lower output, insurance can help reduce the overall welfare loss.

Yet the insurance protection gap in Europe is already substantial, and there are several reasons to suspect it may widen as a result of climate change. More frequent and more severe disasters may act to reduce the supply of private insurance, whilst simultaneously making insurance more valuable from a welfare perspective. Policies aimed at enhancing both adaptation and mitigation of climate-related events are needed to increase the resilience of the economy to climate change. Addressing the structural causes of the protection gap now and in the future has the potential to provide substantial welfare benefits.

While this article provides new insights into the interplay between climate change, insurance, the protection gap and economic output, it also highlights the need for further research. In particular, the role of governments and the potential complementary role of the private sector are key issues with practical relevance, and possible policy implications which should be further explored. While substantial fiscal resources put towards reconstruction can help, this needs to be balanced against the possible effects of creating potentially large contingent liabilities on the balance sheet of fiscal authorities. Finally, while this article focuses on the reconstruction effect that shows up in measured GDP, further work would be necessary to fully understand the effects on welfare.

The potential policy implications of this work also warrant further exploration.[16] The cross-border nature and possible systemic implications of climate change related risks could, for instance, warrant a concerted response at the European level. Knowledge-sharing at European level could enhance risk management and modelling capabilities for natural catastrophes and foster more efficient capital allocation. Risk pooling at regional or European level could potentially improve insurability and affordability. Finally, the penetration of climate risk related insurance could be improved by pairing them with other common or mandatory insurance products.

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[16] See e.g. https://www.ecb.europa.eu/pub/pdf/other/ecb.eurosystemreplyeuropeancommissionpubliconsultations_20200608~cf01a984aa.en.pdf and https://register.eiopa.europa.eu/Publications/EIOPA-19-485_EIOPA%20Staff_Discussion_Paper_Protection_Gap.pdf for reference

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