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Insurance Against Extreme Weather Events: An Overview

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Abstract: Extreme weather events increasingly threaten the economic situation of households and enterprises around the world. Insurance against extreme weather events is among the climate change adaptation instruments that are currently discussed by the policy community. This overview paper provides a synopsis of the state of research on insurance against extreme weather events, outlining advantages and limitations inherent in three main types of insurance: indemnity-based insurance, index-based insurance, and insurance-linked securities. The paper discusses issues related to insurance uptake, distributional effects, misleading incentives and potentially negative side effects, as well as the role of the state.

Keywords: extreme weather events, insurance, insurance-linked securities, indemnity-based insurance, index-based insurance

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1 Introduction

With climate change, the frequency and intensity of extreme weather events, like droughts, heat waves, and heavy rainfall, are predicted to increase (IPCC 2014; WMO 2020). These risks threaten the economic situation of households and

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enterprises around the world, albeit in different ways. In Europe, hydrological events are the most harmful extreme weather events (Kron et al. 2019). In 2021, more than 196 people died during flash floods in western Germany and Belgium (Cornwall 2021). The average economic damage of hydrological events in Europe is estimated at 3.5 billion USD annually over the 1980–2020 period (EM-DAT n.d.). Alfieri et al. (2015) project annual economic flood damage in Europe to rise to 20–40 billion EUR by 2050 in high end climate scenarios. By the end of the century, the number of Europeans exposed to riverine floods may more than double from around 220,000 in the reference period (1981–2020) to 455,000 (Forzieri et al. 2017). In developing countries, most economic damage due to extreme weather events occurs in the agriculture sector (FAO 2018). The average annual economic damage of climate-related disasters in developing countries is estimated at 24 billion USD over the 1980–2020 period (EM-DAT n.d.). In the 2005–2015 period, developing countries experienced a total of 96 billion USD in crop and livestock production losses due to disasters, of which 78% were caused by drought, floods, and other meteorological events (FAO 2018, p. 27). It is expected that the impacts of climate change will push between 32 and 132 million additional individuals into extreme poverty by 2030 (Jafino et al. 2020).

In order to assist households and enterprises in adapting to an increasingly volatile and extreme climate, weather insurance is among the adaptation instruments that are currently discussed by the policy community (Beck et al. 2019; European Commission 2018; Martinez-Diaz et al. 2019; UN Environment Programme 2021). Weather insurance replaces a large, randomly occurring cost of an extreme weather event with a guaranteed cost of the insurance premium. Based on the law of large numbers, insurance combines the risks of many individuals and enterprises, pooling risks across locations and time periods. This way, deviations from the expected loss become less likely and insurance reduces the aggregated risk substantially. In addition, it transfers risks from risk-averse policyholders to more risk-neutral insurance companies. Weather insurance can reduce negative welfare impacts caused by extreme weather events and enable faster recovery. Thus, insurance could be an important option for adaptation to the consequences of climate change for households and companies alike. While insurance against weather risks is not new, the need for adaptation in the context of climate change brought it into the spotlight among both policy makers and researchers.

Despite the positive effects of insurance, to a large extent the losses from extreme weather events are uninsured, not just in the Global South, but also in developed economies. While in high income countries, 45% of the losses from natural catastrophes were insured over the 2008–2017 period, this figure was only 7% in low income countries (based on Munich Re data, see Hott and Tran 2020). One reason for this low level of insurance is that extreme weather events affect many individuals simultaneously and, hence, risks are not independent (referred to as "correlated risks," see Antwi-Boasiako 2014). As a result, risk pooling is significantly limited and insurers must charge higher premiums in order to cover the remaining risk. Another reason for the low insurance penetration is that individuals tend to underestimate the probability of rare events like natural disasters and often hope for public post-disaster relief. Hence, climate change, with extreme weather events increasing in frequency and intensity as a result, might not only increase the need for insurance, but might also make providing insurance more challenging.

This overview paper discusses the role of insurance against extreme weather as a tool to assist households and enterprises in adapting to increasing climate risks. Focusing on three main types of insurance – indemnity-based insurance, index-based insurance, and insurance-linked securities – we discuss issues related to insurance uptake, distributional effects, misleading incentives and potentially negative side effects, as well as the role of the state. In doing so, we consider indemnity-based insurance and index-based insurance in the context of their most relevant markets: property flood insurance for buildings and agricultural insurance, respectively. The paper has two aims: first, it provides a synopsis of the state of research on insurance against climate risk and, second, it outlines advantages and limitations inherent across different types of insurance.

2 Indemnity-Based Insurance

Flood insurance for private homeowners covers damage to residential buildings caused by hydrological events. Such events comprise both river floods and pluvial floods caused by extreme rainfall that either results in surface water floods coming through an overwhelmed drainage system or flash floods characterized by a high velocity torrent of water. Once an extreme event occurs, policyholders must provide proof of the incurred damage to claim payouts from the insurance company, a common feature of indemnity-based insurance. Typically, insurance companies require a deductible as a means to discourage moral hazard (i.e., policyholders have fewer incentives to avoid damage). Flood insurance is compulsory in some OECD countries, but voluntary in others. The extent to which insurance premiums reflect the local level of risk also varies across countries and insurance products. Besides helping policyholders to recover from damage, flood insurance also plays an important role in reducing the total expected damage by financially supporting and encouraging prevention measures. For example, insurance companies cover hazard mitigation upgrades when repairing damaged homes (Kousky 2019). They also provide premium discounts or lower deductibles if policyholders employ technical flood risk reduction measures or settle in relatively safe areas (Craig 2019; Fan and Davlasheridze 2016; Hudson et al. 2016, 2020; Kousky 2019).

Example: flood insurance in Germany ("erweiterte Elementarschadenversicherung")

In Germany, flood insurance coverage is optionally available as one additional module of natural hazard insurance for residential buildings and contents (e.g., furniture, but not cars). The flood insurance module covers damage caused by riverine floods and pluvial floods, which makes it potentially relevant for all areas, even those not located near streams. Flood insurance is always bund led with other rarely occurring natural hazards, like earthquakes, mass move ments, snow load, and avalanches. While the basic natural hazard home insur ance is almost universal in Germany (also due to requirements by mortgaging banks regarding fire insurance coverage), the market penetration of voluntary additional flood insurance amounts to 44% of all residential building contracts as of 2019 (GDV 2020). Compared to other countries, deductibles for German flood insurance are moderate, typically less than 1000 EUR. Premiums are risk-based, hence they are higher for houses in flood-prone areas and there is little (if any) cross-subsidization across risk groups. For the lowest risk class, premiums are on the order of magnitude of 100 EUR per year for an average-sized house; for the highest risk class (houses located in the vicinity of rivers and flooded statistically at least every 10 years), most insurance companies only offer flood insurance on a case-by-case basis, with high deductibles, coverage exclusions, obligations for the policyholder to implement significant risk-reducing measures, and/or high premiums. For homeowners in particularly exposed areas, it may be difficult to obtain flood insurance at all. Most companies require policyholders, irrespective of their individual risk class, to implement and maintain a backflow flap, a medium-cost risk reduction measure that prevents the intrusion of water from the sewage system into the house, to be installed in the basement.

2.1 Problems of Uptakes

In countries with voluntary insurance, take-up rates of property flood insurance are generally low, typically below 50%. This may be an informed and deliberate decision by homeowners to take the risk. However, there are further reasons why households do not take up insurance, which are related to market failure (especially moral hazard and correlated risks), government failure (charity hazard), and individual cognitive limitations (Antwi-Boasiako 2014). One important reason for low uptake related to the latter aspect is the misperception of risk. Low-probability high-impact events, a description common for riverine floods, are often underestimated by decision-makers; hence, insurance premiums reflecting these risks are frequently deemed as too high (Kunreuther and Pauly 2004). In addition, there is little awareness within the population of the risks of pluvial floods in allegedly flood-safe areas. Large-scale awareness campaigns of flood risks and insurance possibilities have been ineffective so far (Osberghaus and Hinrichs 2021). In the German case, the problem is aggravated by the optional inclusion of flood coverage in building insurance. Surveys document that many homeowners erroneously assume that they are, by default, covered against flood damage as part of their standard building insurance contract – hence one may talk of an insurance illusion (Osberghaus et al. 2020).

Another issue is a self-enforcing mechanism based on low insurance density, government relief, and relief expectations. In case of a major flood event striking in an area where many households are without insurance coverage, politicians may feel obliged to support affected households with public flood relief (Antwi-Boasiako 2014). For example, after heavy rains caused major river flooding in Germany in 2013, uninsured private households and businesses received several billion Euro from a tax-financed flood relief fund (Thieken et al. 2016). A similar relief program was implemented after the July 2021 flood in western Germany. It has been documented that such public flood relief increases expectations for financial help in future events, thereby undermining incentives to purchase flood insurance and privately invest in prevention measures (Andor et al. 2020; Kousky et al. 2018). This vicious circle is referred to as natural disaster syndrome (Kunreuther 1996). Of course, no flood relief program can ever ease the non-financial flood losses and impacts.

2.2 Distributional Effects

Property flood insurance can have very different distributional effects, depending on the market structure and characteristics of eventual public relief. If premiums are risk-based, there can be affordability issues, especially amongst inhabitants of high-risk areas, preventing households exposed to the highest risks from purchasing flood insurance (Hudson et al. 2016; Osberghaus 2021). This may result in a higher overall burden among uninsured households, thus potentially creating a divide between insured and uninsured homeowners in the long term. Some studies suggest publicly subsidized insurance premiums, means-tested vouchers, and financial support for risk-reducing measures via low-cost loans or grants to foster insurance take-up by low-income households. If the value of vouchers is independent of the charged insurance premium, insurers may still create incentives for risk reduction by offering premium discounts (e.g., Hudson et al. 2020; Kousky and Kunreuther 2014; Tesselaar et al. 2020).

If premiums are not purely risk-based but more flat, insurance implies a redistribution from policyholders with low flood exposure to highly exposed households. How this redistribution affects income and wealth inequality depends on the eventual sorting of socio-economic groups regarding flood exposure, something that is not clear *ex ante*. In the German case, flood exposure does not correlate substantially with income, hence risk pooling by insurance is not likely to affect economic inequality (Osberghaus 2021).

In general, increasing the insurance market penetration can imply a potentially lower burden on taxpayers and a higher burden on homeowners. In contexts with low insurance market penetration, tax-funded relief funds often step in once a major disaster occurs, which implies an indirect burden on the general taxpayer, including homeowners, tenants, and businesses (Schwarze and Wagner 2007). The benefit of the relief, however, mainly accrues to homeowners. In contrast, a risk transfer system within the insurance market pools the risk amongst policyholders (i.e., only homeowners).

2.3 Misleading Incentives and Potential Side Effects

Like other types of insurance, property flood insurance may suffer from moral hazard. That is, policyholders may behave more carelessly than non-insured individuals; for instance, they may take fewer technical precautions, thereby increasing total damage. However, empirical studies document that, in Germany, there is a positive correlation between the willingness to insure and private investments in technical precautions, hence the risk of moral hazard appears to be limited in this context (Andor et al. 2020; Hudson et al. 2017; Osberghaus 2015).

Some studies caution that insurance may hamper a necessary large-scale societal transformation toward climate resilience by providing a short-term solution (claims settlement) to a long-term problem (increasing vulnerability due to climate change) (Christian-Smith et al. 2015; Müller et al. 2017; O'Hare et al. 2016). Insurance coverage may trigger a false sense of safety amongst policyholders and governments. Payouts from flood insurance in the aftermath of a major river flood actually facilitate the repair and reconstruction of buildings in flood-exposed areas, thereby impeding resettlement to higher grounds. Although not specific to insurance, this effect of adaptive behavior contributing to an increase in climate vulnerability in the long term is referred to as maladaptation (O'Hare et al. 2016).

2.4 Role of the State

Governments intervene in property flood insurance markets in at least three ways: First, they set the regulatory framework for the insurance market. Indeed, there is a wide range of national insurance market designs implemented by governments in Europe and the U.S. (for an overview, see Hudson et al. 2019, 2020; Schwarze et al. 2011). Second, governments have provided post-flood relief or compensation, thus potentially distorting incentives for insurance. Third, through land use planning, governments may effectively increase or decrease flood risk in residential areas; for instance, by developing sites for building in floodplains as well as by restoring or developing wetlands.

Regarding the first aspect, in some countries, insurance is compulsory and often coupled with publicly subsidized flat premiums, which emphasizes the solidarity-based nature of natural hazard insurance (e.g., in France and Spain). In some Swiss Cantons, flood insurance is obligatory and offered by a public monopoly. Compulsory insurance may also be combined with risk-based premiums, but this must include specific solutions for high risk areas, such as a tax-funded catastrophe fund dedicated to existing buildings in these areas. To explicitly secure the ability of households to meet their basic needs and for maintaining incentives for risk reduction, one may also restrict the coverage of the mandatory insurance to the minimum necessary to secure the livelihood of affected households (Osberghaus and Mennel 2014). In the United Kingdom, a nationwide reinsurance scheme (Flood Re) is supposed to keep insurance premiums low and affordable in flood-prone areas. In the case of very extreme events (annuality more than 200 years), the British government has announced it will step in as an insurer of last resort to back up Flood Re. In the U.S., the Federal Emergency Management Agency (FEMA) acts as a government insurer with the National Flood Insurance Program, which is funded by taxpayers' money if premiums do not cover the costs. Furthermore, in other countries there are systems comprising a private and voluntary insurance market that is supplemented by tax-financed catastrophe funds with *ex ante* known payout rules (e.g., Austria) or without *ex ante* regulated disaster relief, but with some experience that the government may step in on an *ad hoc* basis (e.g., Germany and Poland). Some of these market regimes may well include incentives to mitigate flood risks at the household or community level. For example, FEMA evaluates flood mitigation activities of communities and policyholders benefit from high ratings through lower insurance premiums. However, most of the aforementioned approaches – especially publicly subsidized and flat premiums – may undermine the function of insurance as a promoter of risk mitigation.

Given the diversity of feasible regulatory frameworks for property flood insurance, the question arises whether one of the systems is proven to be superior. In an attempt to answer this question, Hudson et al. (2020) use a multi-criteria-analysis to evaluate European flood insurance regimes in terms of insurance penetration, risk signaling, ability to absorb large losses, availability and affordability, as well as smooth compensation procedures. Based on three alternative criteria weighting schemes, Hudson et al. conclude that the systems performing best have in common the bundling of different hazards, such as storms, fire, and floods. Two important mechanisms in these systems are high penetration due to insurance obligations of financing banks and a higher degree of risk pooling capacities by a combination of different natural hazards.

Regarding the second aspect, the role of the state in post-disaster relief, there are suggestions that different layers of risk should be dealt with by different actors (Keskitalo et al. 2014): minor damage should be absorbed directly by policyholders (e.g., through deductibles), insurance companies should cover medium-sized losses, and the government would be responsible for covering very large losses, as a last resort solution to extreme damage, as the costs for (re-)insuring these extreme events on the private market may be too high.

3 Index-Based Insurance

Agricultural insurance has the potential to protect the well-being of large numbers of rural farm households (Barnett and Mahul 2007). Yet, indemnity-based agricultural insurance, in which payouts are determined through on-site loss verification, not only failed in most developing countries (Jensen and Barrett 2017; Platteau et al. 2017), but also in most developed countries (Miranda and Farrin 2012). Besides high mark-ups on actuarial fair premiums to cover the fluctuation of aggregated losses (see Introduction and Gollier 1997), the main reasons are high transaction costs incurred by costly visits of insurance agents to policyholders living in remote rural areas, especially if infrastructure is poor, the difficulty of policyholders to document property rights over (destroyed) assets, as well as moral hazard and adverse selection (Mahul and Stutley 2010; Skees and Barnett 2006).

Index-based insurance (also referred to as parametric insurance) is designed to overcome these constraints. Since the late 1990s, it is gaining traction in developing countries and is currently discussed in the policy community with high hopes (Cai et al. 2021; Fisher et al. 2019; GPFI 2015; Greatrex et al. 2015; Hazell and Hess 2017). In index insurance, payouts to policyholders depend on an index that strongly correlates with losses in income or assets. Existing index insurance schemes use data on, for instance, precipitation, vegetation greenness, average crop yields, and livestock mortality to construct the index. The index is calculated at an aggregate geographic level, such as the region or district. Policyholders receive insurance payouts whenever the index exceeds or falls short of a predefined threshold, irrespective of whether or not a specific policyholder experienced damage. As individual loss verification is not carried out in index insurance, transaction costs are significantly lower compared to indemnity-based insurance, which potentially makes index insurance more affordable (Miranda and Farrin 2012). In addition, index insurance avoids moral hazard, as policyholders with below-average losses still benefit from payouts when the threshold is reached at the aggregate geographical level. The main challenge in index insurance is basis risk (i.e., the risk that the policyholder incurs damage but the insurance does not provide payouts or that the insurance pays even though there is no damage). Hence, it is important to identify a suitable index that is highly correlated with damage while at the same time builds on reliable data that are accessible with little time lag and inexpensive (Mahul 2001; Teh and Woolnough 2019).

The welfare-enhancing effects of index insurance are documented in various developing countries. On the one hand, payouts from index insurance in the wake of an extreme weather event helped policyholders in Mongolia recover from asset losses (Bertram-Huemmer and Kraehnert 2018). Payouts also helped households in Kenya to avoid asset-depleting shock coping strategies, such as selling productive assets and compromising their nutrition (Janzen and Carter 2019). On the other hand, it is shown that purchasing index insurance enables households to engage in more profitable, yet more risky, agricultural investments that increase household welfare even if no extreme weather event occurs (e.g., Cai 2016; Hill et al. 2019).

In developed countries, index insurance is still a niche product. In Germany, examples of index insurance products include insurance against rainy days during holidays and insurance for organizers of open-air events against bad weather (Achtnicht and Osberghaus 2019). Index insurance can be an alternative when conventional, indemnity-based insurance products are unfeasible. This is typically the case in the agricultural sector. For instance, in Austria, Canada, Germany, Switzerland, and the U.S., index insurance for grasslands emerged, where yields are difficult to measure (Vroege et al. 2019). Recent studies explore the potential for index insurance in developed countries. Kath et al. (2018) construct an index based on winter precipitation for Australia to explain variation in wheat yield losses due to droughts. Results suggest that winter rainfall could be a financially efficient index for several of Australia's wheat growing regions. Hott and Regner (2021) evaluate the potential benefit of index insurance for German crop farmers. They find that index insurance based on mean summer temperature could be an efficient tool to manage climate-related financial losses among German farmers.

Example: index-based weather insurance in Mongolia

One of the first agricultural index insurance schemes worldwide that was scaled up to the national level is Mongolia's Index-based Livestock Insurance (IBLI). Developed with technical assistance from the World Bank, IBLI was first introduced in selected pilot areas in 2006 (Mahul and Skees 2007). Since 2012, it is available in every district of the country, with IBLI policies being sold by various commercial Mongolian insurance companies. IBLI provides protection against livestock losses, the backbone of the rural economy. High livestock mortality due to extreme winter conditions, such as extremely cold temperatures and excessive snowfall, is the main economic risk to pastoralist households that tend animals to generate income, produce food, and store wealth.

In IBLI, the index for triggering insurance payouts is the livestock mortality rate in the policyholders' district of residence. The index is constructed from the annual Mongolian Livestock Census, which is collected every December by the National Statistical Office of Mongolia (NSO) since 1918, and a livestock survey implemented by the NSO each year in June that records the number of deceased animals. Based on the publicly available livestock data, the annual livestock mortality rate is calculated for each district and each of the five common species (goats, sheep, cattle, horses, and camels). Whenever the district-level mortality of a species exceeds 6% in a given year, then all policyholders residing in the district receive a payout from IBLI, irrespective of whether or not a policyholder actually experienced any livestock losses.

Households can purchase IBLI between January and June in a given year. IBLI contracts cover weather risks occurring during the following winter, between December and June of the following year. Households decide for which of their species, for how many animals of each species, and for how much of the animals' market value (1–100%) they purchase insurance coverage. Premiums differ slightly across districts, capturing differences in local risk. The payout amounts are determined by the exact district-level livestock mortality rate and the animals' market value that a household insured. In 2020, more than 28,000 Mongolian households purchased IBLI policies for about 7 million animals, representing a market penetration of about 17%. Policyholders spent an average of 37 EUR on IBLI premiums in 2020 (Mongolian National Reinsurance 2021), about 1% of households' annual income (National Statistical Office of Mongolia 2021).

3.1 Problems of Uptakes

In developing economies, uptake rates remain low despite the fact that index insurance premiums are almost universally subsidized through vouchers or premium reductions (Carter et al. 2018). The demand for index insurance is also low in OECD countries. Several factors are identified to explain this pattern. Among these is the presence of basis risk. A study in Mali shows that high basis risk reduces the demand for index insurance, as it discourages those farmers that did not receive payouts despite experiencing damage (Elabed et al. 2013). Another factor identified to explain low demand for index insurance is households' liquidity constraints. A study in Ethiopia documents that despite their general willingness to pay for insurance, farmers decide against purchasing index insurance due to the timing of the insurance premiums, which overlaps with the time when households are most cash-constrained (Patt et al. 2009). Low levels of trust in the insurance provider is also identified as another reason for low uptake (Giné et al. 2010).

Additionally, individuals have difficulties assessing the probability that a natural disaster will strike and, in turn, that payouts from index insurance will be triggered. According to Botzen and van den Bergh (2012), individuals follow a Bayesian updating when assessing risks (i.e., they base their probability assessment on recent observations) and, therefore, might increase their willingness to pay if the frequency of extreme weather, and thus the likelihood of having recently been exposed to such an event, increases. Using three waves of a household panel survey, Mogge and Kraehnert (2021) find that Mongolian households are more likely to purchase index-based livestock insurance if they were exposed to harsher weather conditions in the previous winter. Empirical evidence for this mechanism is also documented for the U.S. (Gallagher 2014) and rural China (Cai and Song 2017). Other studies caution that this mechanism only applies to developed economies (Hott and Tran 2020).

Another hurdle for the market penetration of index insurance is that individuals are not familiar with this kind of insurance product and, thus, might hesitate to purchase it. Drawing on a household survey implemented in Germany, Achtnicht and Osberghaus (2019) find that German homeowners are rather skeptical about flood index insurance. Similarly, empirical evidence suggests that index insurance products are not easily understood by farmers in the Global South, who often have low financial literacy, which reduces uptake (Giné et al. 2010). Tailored market regulation can contribute to increasing trust in index insurance products and stimulate demand (Hott and Tran 2020).

3.2 Distributional Effects

Index insurance schemes that are not equally accessible to all households in a given community, region, or country may have unintended distributional effects. In the context of developing countries, one concern is that both the overall amount of insurance premiums and the timing of premiums may prevent the poorest households from accessing index insurance (Hill et al. 2013; Patt et al. 2009). Consequently, in times of climate distress, uninsured poor households may be forced to sell their productive assets at unfavorable market prices, while insured households are better positioned to recover quickly. This scenario can have implications for the accumulation and distribution of wealth in the short and long term. Some researchers also question more generally if formal insurance (whether index-based or indemnity-based) is an appropriate adaptation instrument for the poor in developing countries (Binswanger-Mkhize 2012; Chantarat et al. 2017; Fisher et al. 2019).

Distributional issues of index insurance may also have a gender dimension. Insurance products may not be equally accessible for men and women, as the specific constraints facing rural women, such as higher financial illiteracy, less access to information, and preferences for certain financial institutes, may lower the demand for insurance among women (Akter et al. 2016; Born et al. 2019). Another concern with regards to the distributional effects of index insurance is the role of technological innovation in insurance markets. While innovations, like the use of mobile phones, have the potential to revolutionize insurance market services (Hazell and Hess 2017), they may disadvantage poor farmers who do not have access to such technologies (Baumüller 2012).

3.3 Misleading Incentives and Potential Side Effects

Currently, to expand the market penetration of index insurance, a growing number of pilot projects are being implemented in developing economies around the world (Di Marcantonio and Kayitakire 2017). However, scaling up index insurance may result in unintended ecological effects. For instance, by transferring risk to a third party, policyholders are likely to start engaging in high-risk, high-profit production activities, including greater agricultural input use as well as intensified livestock- and monoculture systems. While this has welfare-enhancing effects for policyholders, it entails the risk that index insurance coverage may incentivize insured households to use land and other ecological public goods in unsustainable ways, focusing on short-term economic benefits (Müller et al. 2017; Quaas and Baumgärtner 2008). The long-term effects of environmental pollution due to intensified use of agrochemicals (Hill and Viceisza 2012; Sibiko and Qaim 2020) and land degradation may, in turn, increase the climate vulnerability of rural communities, especially for those households without access to insurance. Empirical evidence on the impact of index insurance uptake on existing informal risk sharing networks points in different directions. On the one hand, informal transfers to policyholders increased in Ethiopia ("crowding-in") (Takahashi et al. 2019). On the other hand, informal transfers to persons in need who do not hold formal insurance were found to decline in Cambodia ("crowding-out") (Lenel and Steiner 2020). Moreover, index insurance may have unintended negative impacts on household dietary diversity (Habtemariam et al. 2021).

3.4 Role of the State

Governments in the Global South have intervened in the market for index insurance in several ways – most prominently by subsidizing insurance premiums. Other forms of governmental interventions include creating an enabling legal framework, reducing informational asymmetry, providing infrastructure support, as well as increasing awareness of risk and the role of insurance (Mahul and Stutley 2010).

Post-disaster support provided by governments and aid organizations may interfere with insurance markets by reducing farmers' willingness to participate in insurance programs (Mahul and Stutley 2010). For instance, Sakurai and Reardon (1997) find evidence that, in Burkina Faso, expectations of public food aid decrease the demand for drought insurance. However, in many low-income settings, post-disaster assistance tends to be patchy and is only available in times of large-scale catastrophic events.

Some governments aim at fostering index insurance coverage by bundling index insurance with credit services and with the purchase of agricultural inputs, either on a voluntary or mandatory basis. This is often pursued in collaboration with micro-finance institutes and input suppliers. Linking insurance with credit services can increase insurance uptake by reducing liquidity constraints to pay for insurance, while insurance increases the credit worthiness of farmers by serving as a collateral. Among the countries that tested some variants of bundling of index insurance with credit and input services are India, Philippines, Mali, Senegal, and Kenya (Defiesta and Mediodia 2016; Duchoslav and Van Asseldonk 2018; Meyer et al. 2019; Mukherjee et al. 2017).

4 Insurance-Linked Securities

A key challenge of insuring extreme weather events is that such risks are difficult to pool at the national level (see Introduction). One way to address this challenge is to widen the pool to an international or global scale. Another way is to diversify climate risks with other risks. Financial markets can support both solutions by facilitating the global allocation and diversification of risks, commonly referred to as insurance-linked securities (ILS). According to Hofmann and Pooser (2017), ILS are financial instruments whose value is linked to multiple forms of insurance risks. While there are also ILS linked to insurance risks like mortality risk, ILS are mainly known for securitizing risks related to natural disasters (Anderson and Baxter 2017). Currently, there are principally two kinds of ILS providing insurance against extreme weather events: catastrophe bonds (cat bonds) and weather derivatives; these differ in the way they work and in their focus.

The main idea of catastrophe bonds is that someone who is exposed to extreme weather events (e.g., a company, a government, or an insurer) issues a cat bond. Investors in this cat bond receive an interest rate payment (like an insurance premium), but must cover losses in case a pre-defined event materializes. Such an event can either be a large-scale economic loss that exceeds a pre-defined value or an extreme weather condition that exceeds a pre-defined threshold (Hofmann and Pooser 2017). In reality, catastrophe bonds are mainly used for reinsurance purposes. An insurer transfers the risk to special purpose vehicles (SPVs) – a separate legal entity that enables the separation of the risk from the insurance company. In exchange, the insurer pays a premium to the SPV (Charpentier 2008). The SPV then issues securities (the cat bonds) to finance the coverage.

Weather derivatives cover a broader range of weather risks and are designed to insure end customers, such as farmers, ski resorts, and construction companies (Hofmann and Pooser 2017). Weather derivatives are tradable contracts between two parties (e.g., a call option, a put option, or a future contract) that specify under which conditions payouts are triggered (strike level) and set the upper limit of payouts (notional value) (Alexandridis and Zapranis 2012; Till 2015). The price of a weather derivative is driven by its expected payout. Unlike most other derivatives, weather derivatives are not based on a tradable underlying asset, but rather on a weather index. This weather index is based on recordings (e.g., temperature, rainfall, or wind speed) at a pre-specified weather station. An additional difference to other derivatives is that weather derivatives are usually used to hedge volume risks (e.g., wind speed is highly correlated with the amount of energy a wind farm produces), rather than price risks on the market (Müller and Grandi 2000). Hence, the combination of classic market price-driven derivatives and weather derivatives could be well suited for holistic risk management.

As insurance-linked securities are often based on a weather index, advantages and disadvantages are comparable to those inherent in index insurance. Insurance-linked securities avoid problems of moral hazard and adverse selection, but entail basis risk. In contrast to index insurance, insurance-linked securities are tradable, which leads to additional positive and negative effects. On the positive side, transferring insurance risk into insurance-linked securities (i.e., securitization) increases the liquidity of the risk instrument as it can relatively easily be sold or bought on the market. Furthermore, securitization facilitates access to a wider range of risk takers, such as banks or companies, with a different risk profile. For example, different sectors might be exposed to opposite weather risks: While a dry and very sunny summer might have a negative effect on agriculture, it could have a positive effect on the beverage industry and solar energy producers. Hence, these sectors could take opposite positions on the weather derivative market. On the negative side, using insurance-linked securities requires more financial expertise. In addition, securitization can make the market more opaque because it is not always clear who is holding which risks.

Example: weather derivatives for renewable energy
Weather derivatives were first introduced in 1996 to hedge weather risks of energy suppliers in the U.S. (Alexandridis and Zapranis 2012). Since the demand for energy is high if it is either abnormally cold in winter or if it is abnormally hot in summer, weather derivatives that are based on temperature are well suited for the risk management of energy suppliers (Müller and Grandi 2000).
In the renewable energy sector (e.g., wind and solar energy), both energy demand and energy production heavily depend on weather conditions. Hence, they are subject to a risk that cannot be insured via indemnity-based insurance. Hedging or eliminating this weather risk would reduce income volatility among energy suppliers, make investments in renewables more attractive, and facilitate the access to bank loans. Following Hain et al. (2018), quantity-related weather contracts have the potential to manage weather risks of renewable energy producers.

Wind energy is affected by different wind risks, as wind speed can be too low or too high (Benth et al. 2018). Hence, a combination of wind derivatives that cover too low and too high wind speeds could help to hedge the risks of wind energy production. In 2019, for example, ENEL Green Power – the U.S. renewable energy daughter of the Italian ENEL – hedged the risks of its largest wind farm project through a derivative that combines price and wind risks (Boyle et al. 2021). In general, however, the market for wind derivatives is growing slowly on a low level.

4.1 Problems of Uptakes

While the cat bond market has developed relatively well and has become a vital pillar of the risk management of insurers (Cummins 2008), weather derivatives still seem to be a niche product, at least outside the U.S. (Musshoff et al. 2011; Salgueiro and Tarrazon-Rodon 2019). There is also a difference between the U.S. and the rest of the world with respect to cat bonds. While in the U.S., the number of outstanding cat bonds more than doubled between 2010 and 2017, across the rest of the world, the amount was lower in 2010 than in the U.S. and remained there (Polacek 2018). Since 2014, the World Bank issues cat bonds to cover risks from natural disasters in the Global South.[1]

Accessing insurance-linked securities to cover potential losses from climate risks requires a certain know-how and infrastructure. While this is also true for indemnity-based insurance or index insurance, it is particularly relevant for insurance-linked securities and constitutes a major hurdle for some households, farmers, and companies (UNFCCC 2008).

Weather derivatives also entail a counterparty risk, i.e., the risk that the counterparty will not be able to fully meet its obligations. While this is, to some degree, also true for indemnity-based insurance, counterparties of derivatives are not necessarily regulated (to the same degree). As demonstrated by Härdle and Osipenko (2017), this counterparty risk significantly depresses the demand for weather derivatives. In this vein, Alexandridis and Zapranis (2012) highlight that the Chicago Mercantile Exchange supported the development of the weather derivative market by eliminating counterparty risk (via guarantees).

4.2 Distributional Effects

Since acquiring knowledge about insurance-linked securities constitutes fixed costs, there are economies of scale. Hence, it is much easier for larger companies to use these tools and protect themselves against risks than for smaller ones. Insurance-linked securities can cover risks that would otherwise have been uninsured. Hence, these instruments potentially increase the welfare of risk-averse individuals and facilitate investments.

4.3 Misleading Incentives and Potential Side Effects

Given that weather derivatives are based on an index and not on actual losses, moral hazard should be limited. However, the fact that the risks are securitized can create new risks and misleading incentives. The mortgage-backed security market

1 https://blogs.worldbank.org/voices/disaster-risk-using-capital-markets-protect-against-cost-catastrophes.

and the global financial crisis provided some hints on how this can happen (Hott 2011). There is, for example, often an incentive to securitize risks in order to lower capital requirements. This is, to a large extent, based on a lower liquidity risk (risk can be sold on the market). However, in a major crisis, liquidity can dry up quickly and capital levels of investors might, therefore, be too low to cover losses. Hence, misleading incentives can not only inflate insurance-linked security markets, but can also increase counterparty risks. Another problem can arise from the fact that information and levels of expertise are asymmetric between the issuer of a cat bond and investors on the secondary market. In addition, Pérez-González and Yun (2013) show that the usage of weather derivatives provides an incentive to increase both investments and leverage, thus also increasing risk taking. However, this is a moral hazard problem that may also arise in other types of insurance.

The success of transferring climate risks to the financial market depends on the correlation with other financial market risks as well as the risk-bearing capacity of the financial market. On the one hand, there is the danger that the climate risks end up with investors who are unable to pay in the case of a severe weather event. On the other hand, there is the abstract danger that an extreme weather event may harm the stability of financial markets. Several studies analyze the development of insurance-linked securities over time. While Braun (2016) concludes that prices for cat bonds are mainly driven by underlying risks, Gürtler et al. (2016) find empirical evidence that cat bond prices are also influenced by financial crises. Similarly, Weagley (2019) shows that weather derivatives are not only influenced by fundamentals, but also by general financial sector stress.

4.4 Role of the State

The role of the state for insurance-linked securities is similar to that of index insurance. On the one hand, public post-disaster relief can crowd out insurance-linked securities. On the other hand, the state can support these markets by setting adequate standards, thereby reducing hurdles for households, farmers, and companies. Potentially, a good example of the latter is the Capital Markets Union (CMU) project of the European Union. The aim of this project is to facilitate access to capital markets, thus broaden the funding base of SMEs across Europe. Intended measures, such as setting up platforms, reducing administrative and regulatory burdens, as well as harmonizing standards across Europe would also foster the usage of insurance-linked securities in the EU. For states in the Global South, activities of the World Bank, which has issued cat bonds for countries like Jamaica, Mexico, and the Philippines, are crucial to introduce (reinsurance) protection via cat bonds.

5 Discussion and Conclusion

From this review of the current state of research on insurance against extreme weather events, we formulate a number of policy recommendations. It should be stressed that we do not unconditionally advocate weather insurance as a climate adaptation instrument for households and enterprises around the world *per se*. Rather, we caution that the potential of weather insurance strongly depends on the empirical context. This includes, for example, the overall living standards of a given country, the economic well-being of specific population subgroups, the availability of public safety nets (independent of extreme weather risk) for the poorest part of the population, characteristics of the local insurance market, and the risk to be insured. The following points should be taken such that if policy-makers desire to increase the take-up of insurance, then the aspects outlined below ought to be considered.

There is a need to inform the public about the design of weather insurance products and the risks of extreme weather events. One obstacle for insurance take-up is the common lack of understanding of the design of weather insurance products, which – for instance, in the case of index-based weather insurance and cat bonds – are often innovative products that differ from conventional indemnity-based insurance. Hence, sensitizing the public about the product design, the layering of risks, potential basis risk that is not covered by insurance, and the national regulation of the insurance market is warranted. This is particularly important in the context of developing countries, where financial literacy is often low. Lastly, the acceptance of, and demand for, weather insurance products require an increased awareness in the population regarding the risks of extreme weather events under climate change.

Public post-disaster relief should follow pre-defined guidelines and must be communicated transparently. Given the unpredictability of past governmental post-disaster relief and the resulting disincentives for private insurance demand, there are several arguments in favor of reforming ad-hoc public relief payments. Clearer communication and specification of expected aid payments, for instance through legally binding guidelines, would reduce uncertainties about public aid payments, thus making the benefits of private risk reduction more calculable for households.

Weather insurance should encourage private adaptation measures. Weather insurance products need to be (and in many cases are already) designed such that the insurance inherently provides incentives for policyholders to privately engage in risk-reducing behavior, for instance through risk-based premiums or deductibles. Risk-based premiums may serve as an especially important instrument to communicate about weather risks and raise the awareness of associated costs, for instance of settling in a flood-prone area. They also have the potential to promote the installation of risk-reducing measures in existing buildings. However, in case of risk-based premiums, there is a need to closely monitor the potential unaffordability of insurance – especially if economically deprived population subgroups tend to locate in high-risk areas. To make insurance affordable to low-income households and maintain incentives for risk-reduction, policymakers could, for instance, provide means-tested vouchers for insurance that are independent of the risk level or direct support (through grants or low-cost loans) for risk reduction measures.

Weather insurance needs to be complemented with public adaptation measures. Policymakers should not regard insurance as a substitute, but as a complement to other climate adaptation measures. Those could comprise technical measures, reserving natural areas for flooding, nature-based solutions to prevent flood damage on residential buildings and farm land, improved farm management to mitigate damaging climate impacts on agricultural yields, and early warning systems, among others.

Research has an important role for the future development of weather insurance by informing about the costs and benefits, the unintended side effects, and the product design. Future research is particularly warranted in the following three areas. First, there is need for empirical research that evaluates in which contexts and circumstances insurance is effective in assisting households to recover from weather-induced damage. Such information could be used to evaluate the need for additional relief schemes, calculate premiums, and inform the layering of risk across policyholders, insurance companies, re-insurers, and the government. Second, future research should quantify potentially negative side effects of weather insurance, for instance in terms of ecological damage and its distributional effects. Understanding these effects will help improve the design of insurance markets in terms of incentive structures. Third, the availability of weather data via a dense network of weather stations or satellite images is crucial for pricing insurance products and projecting future risks. In the special case of index insurance, research can reap the benefits of open source data and define new relevant indices at low cost (e.g., Arumugam et al. 2020).

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