1 IN 1000

HOW CLIMATE STRESS-TESTS MAY UNDERESTIMATE FINANCIAL LOSSES FROM PHYSICAL CLIMATE RISKS BY A FACTOR OF 2-3x

About 1in1000

1in1000 is research collaboration between Oxford Sustainable Finance Initiative and Theia Finance Labs (Formerly 2° Investing Initiative Germany) that brings together new & existing research projects on long-termism, climate change, and (inter-)connected future risks for financial markets, the economy, and society. Its objective is to develop evidence, design tools, and build capacity to help financial institutions and supervisors to mitigate and adapt to future risks and challenges. The programme focuses on climate change (inter-) connected risks and challenges, notably risks stemming from ecosystem services, as well as risks from social cohesion and resilience.

About Theia Finance Labs

Theia Finance Labs (formerly 2° Investing Initiative Germany) is an independent, non-profit think tank incubating research solutions for the financial sector that help solve the climate crisis. The Theia Finance Labs name is inspired by the Greek goddess of sight, the light of the blue sky, and the value of gold, Theia, and by the Greek word Aletheia, which means "disclosure" or "truth", literally "the state of not being hidden". The new brand thus mirrors our goal to develop evidence-based research and tools that shed light on the intersection of finance, climate change, and long-term risks. Theia operates as a 100% non-profit organization.

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Executive Summary

The current results of climate stress-tests conducted by financial supervisors and the private sector suggest that climate-related risks are less pronounced than 'traditional' risks assessed as part of 'normal' stress-test exercises.

Current estimates around potential financial losses from physical climate risk oscillate around 5-10%, although certain institutions may have higher results. By being more 'conservative' in the models underpinning these approaches, they cater to the sensitivities of the central banks developing them. However, as a result, they also may hide more extreme outcomes (University of Exeter 2023).

A key challenge in interpreting these outcomes is the extent to which these exercises are limited in their scope of application.

Climate stress-tests (or scenario analyses as they are sometimes called) typically build on the NGFS "Hot House" scenario. There a number of challenges to this approach however:

- The scenarios represent a 'central' estimate under a high-carbon future and not some of the more pessimistic outlooks about the potential economic dislocation that higher temperature outcomes may bring.
- They typically do not consider the additional effects of climate tipping points (physical or social).
- They similarly understate climate risks at lower temperature outcomes as being effectively negligble.
- Finally, these scenarios focus exclusively on direct climate impacts and do not take into account the potential social or ecosystem shocks that may arise as a result of climate change.

This paper seeks to identify the potential levels of financial losses under a more proper 'stress-test' scenario for equity markets, focusing on the integration of climate, as well as social and ecosystem tipping points.

The paper combines academic research on the potential GDP effects of climate change with and without climate tipping points, ecosystem service loss, and social tipping points. It aggregates these risks to develop alternative GDP pathways until 2050 where risks from these factors materialize. These alternative growth pathways are then plugged into a multi-period discount dividend model to simulate implied valuation losses or lower return implications of these scenarios.

The models and calculations used here are by design rudimentary.

We describe the approach in this paper as "quantiative heuristics". We do not provide a fully developed, integrated economic model, but rather build a simple GDP and discounted cash flow model that is shocked based on the estimates of economic impacts of the these different "tipping points" on GDP, sourced from third party literature. The effects are aggregated and then integrated into a "global discounted cash flow" that seeks to estimate the loss in future asset value in terms of today's net present value. The simple approach allows for a clean isolation of different potential tipping points individual effects as well as a clear communication on the findings. Crucially, the analysis is not an attempt to quantify mispricing, but simply the delta in net present value of equity markets under a 'no impact' and 'impact climate estimate.

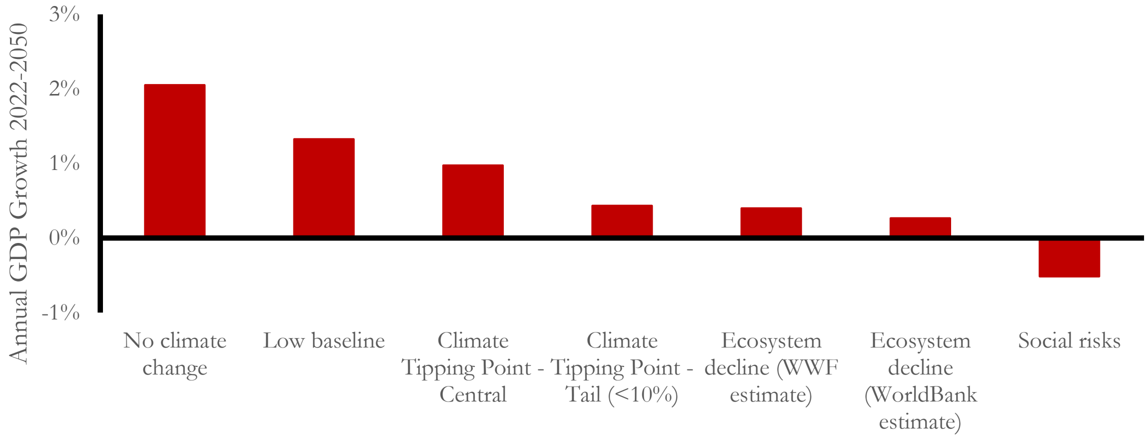
While this report seeks to provide a broader basis for discussion about climate risks, it recognizes that it too may understate the total impacts. The ultimate economic impacts of climate tipping points is contested (Carbon Tracker Initiative 2023). What is more, dramatic economic shocks will obviously not just impact the valuation through lower cash flows but also higher long-term risk premia (the subject of an upcoming report). Our "quantitative heuristics" isolates the pure "economic" impacts and how they pass through to cash flows and thus provide a clear indication of the potential effects of these tipping points.

They are developed based on third-party academic and grey literature, and historical shocks involving similar events where they exist. Despite the uncertainty of these estimates, including them likely represents a more complete picture of what a "climate stress-test scenario" should or could look like.

Integrating social, ecosystem and climate tipping points into stress-tests could generate long-term negative growth rates.

The Fig. below highlights the estimated GDP growth pathways until 2050 under a no climate change baseline and the cumulative effects of climate change, climate tipping points, ecosystem declines, and social risks. The results highlight that the most extreme scenario involves effectively long-term negative growth over the next three decades.

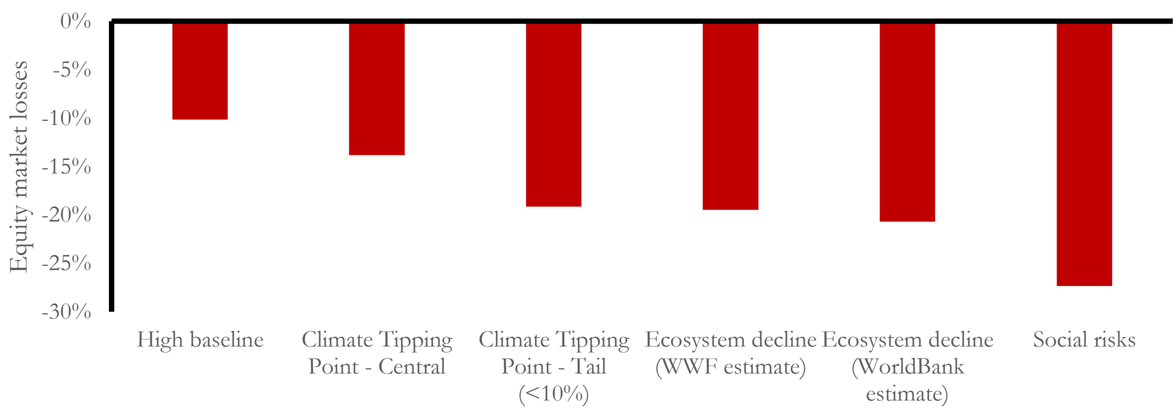
Fig 0.1: GDP growth under a cumulative climate, ecosystem, and social stress-test scenario (Source: Authors, based on Dietz et al. 2019, de Groot et al. 2022, SwissRe 2021, 2DII 2019)



Our findings suggest that climate tipping points, ecosystem (including biodiversity) decline, and social risks have the potential to amplify the financial losses in equity markets from climate change by a factor of 2.5-3.5x.

A high baseline climate risk (i.e. using a climate stress-test model with meaningful baseline GDP losses over the next 30 years) stress-test scenario can create a 10% shock to global equity markets. A combination of climate tipping points, ecosystem decline, and social risks can increase that number as a cumulative risk to 27%, almost 3x the baseline losses. A low baseline scenario of a 4% shock in turn turns into a 14% shock when considering these other factors. These losses are dramatic as they are secular and not cyclical. It is worth flagging that this event would be unprecedented in modern financial market history.

Fig 0.2: Cumulative global equity market losses under a cumulative climate, ecosystem, and social stress-test scenario (Source: Authors, based on Dietz et al. 2019, de Groot et al. 2022, SwissRe 2021, 2DII 2019)



I. Introduction

Climate stress-tests and scenario analysis exercises by central banks are designed to identify potential risks of climate change and the transition to a low-carbon economy. These exercises may identify one of two outcomes

- Lower long-term risk-adjusted returns potentially reduce the long-term resilience of the financial sector;
- A sudden internalization of externalities may create financial dislocation that creates a financial crisis

The first issue is one that warrants supervisory intervention where supervisors understand their role to ensure optimal capital allocation in financial markets from either an economic policymaking perspective and / or the objective of contributing to a more robust long-term financial sector. The second issue may be material from a financial stability perspective, depending on the overall scale of dislocation, and by extension relevant for supervisors and central banks with a stability mandate.

The current results of climate stress-tests conducted by financial supervisors and the private sector suggest that climate-related risks are less pronounced than 'traditional' risks assessed as part of 'normal' stress-test exercises.

Current estimates around potential financial losses oscillate around 5-10%, although certain institutions may have higher results. However, the underlying scenarios are in fact not typically extreme in the sense that they represent tail outcomes. As a result, these exercises may not meaningfully be considered 'stressors' to the system. Rather, they are typically consistent with the *central* estimates of the climate policy and modelling community around future trajectories under various scenarios. As a result, there is an inconsistency between the logic of stress-tests designed to identify potential *tail* or *low-probability* events that may be financially material, with the current suite of scenarios used in climate stress-test that in fact – for a given future (e.g. 1.5°C or 4°C) represent the central estimate as to how the future will materialize. In addition, their view of 'externalities' is narrow and does not capture the secondary effects of ecosystem decline and societal risks that may both be driven by climate change and in parallel reinforce the economic damages related to climate change. Capturing the compounding nature of these different drivers is essential.

A key challenge in interpreting these outcomes is the extent to which these exercises are limited in their scope of application.

Climate stress-tests (or scenario analyses as they are sometimes called) typically build on the NGFS "Hot House" scenario. There a number of challenges to this approach however:

- The scenarios represent a 'central' estimate under a high-carbon future and not some of the more pessimistic outlooks about the potential economic dislocation that higher temperature outcomes may bring.
- They typically do not consider the additional effects of climate tipping points.
- They similarly understate the climate risks at lower temperature outcomes as being effectively negligible, given their focus of climate risks at higher temperature outcomes.
- Finally, these scenarios focus exclusively on climate and do not take into account the potential social or ecosystem shocks that may arise as a result of climate change.[1]

This report represents the first attempt to bring together the potential financial risks that come from tail scenarios and tipping points linking climate, ecosystem, and social risks.

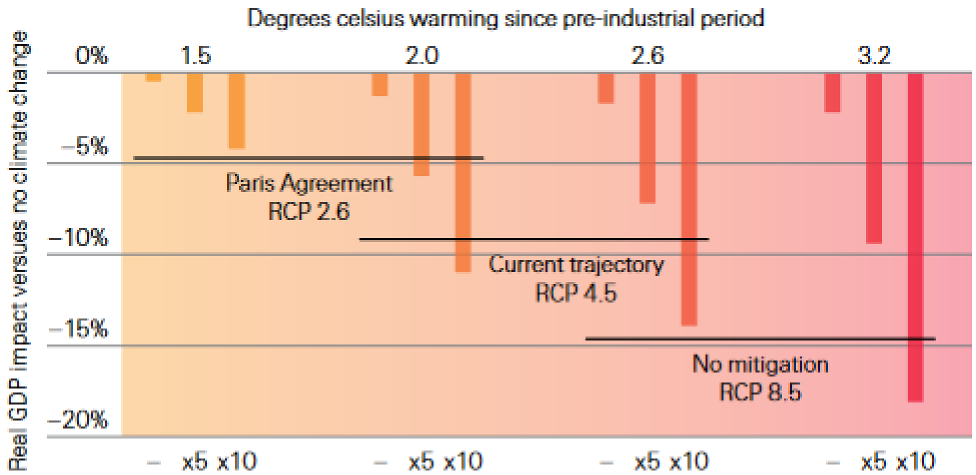
[1] https://iopscience.iop.org/article/10.1088/2752-5295/ac856f and https://openknowledge.worldbank.org/handle/10986/37041

II. Approach

This paper explores the potential increased financial materiality related to what we call 'tail' physical risk scenarios based on a combination of heuristics and a simplified model approach, ecosystem decline, and societal conflict. The following summarizes the components of the model:

- **Baseline estimates.** The paper will use two baselines: The SwissRe baseline and the 2DII previous stress-test scenario baseline (2019). We use SwissRe 2021 research to identify the baseline GDP impacts of climate change by 2050 based on estimated warming of 2.3°C. SwissRe represents these estimates based on baseline projections and "(un)known unknowns" which it uses as multipliers to their projections (5x and 10x). The challenge with these multipliers is that they may duplicate partly with the issues covered in the other factors. However, overlap is likely limited given that the description does not cover the issues identified in this paper. We will use the baseline of 2°C warming by mid-century with the "moderate" multiplier of 5x (covering supply chain disruptions etc.). The more dramatic extreme scenario from SwissRe is largely consistent with the 1in1000 stress-test model from 2019 ("Storm Ahead). The use of these baselines was chosen given their clear reference to temperature outcomes and the desire to compare one 'industry' estimate (SwissRe) in relation to our own exercise. The two approaches can largely be considered the two boundaries of the literature in terms of effects (recognizing that some studies also find no economic impact of climate change)

Fig. 2.1: Economic impact of climate change by mid-century under various warming scenarios (Source: SwissRe 2019)



Note: – refers to no simulated parameter uncertainty. x5 and x10 represent the increasing severity of potential outcomes from (un)known unknowns.
Source: IPCC AR5, Swiss Re Institute

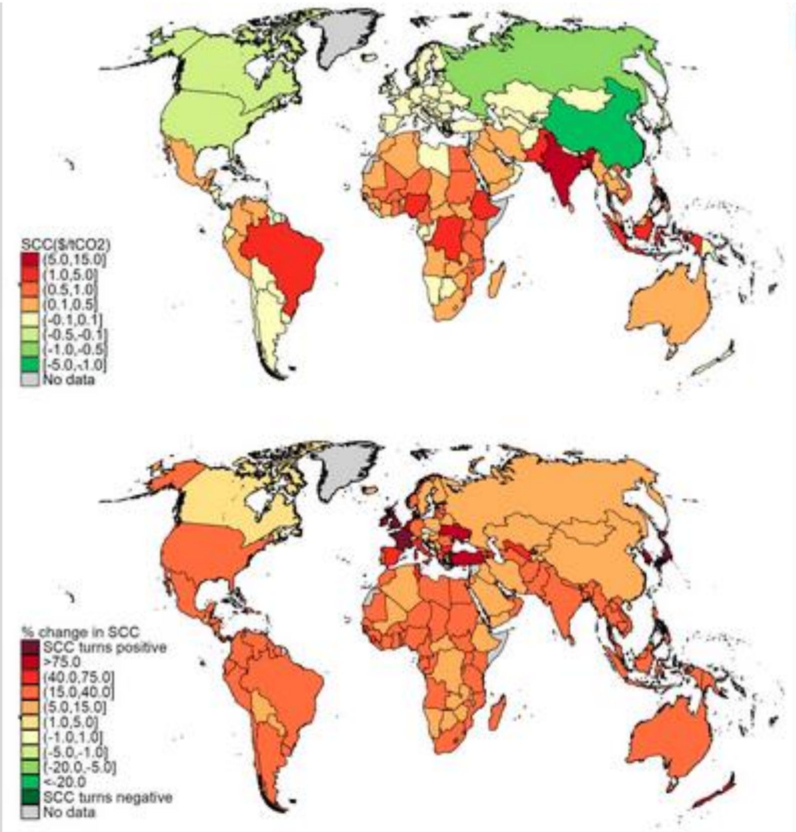
- **Climate tipping points:** The first component is to identify the additional ramification of climate tipping points. Climate tipping points have a range of different effects on the environment and the planet's response to global warming. In our analysis, we seek to add these effects to the baseline or high climate scenario risk models outlined above, given that these do not consider climate tipping points.

  The additional GDP shock is extrapolated from a study by Dietz et al. that estimates the economic impacts of climate tipping points on social costs of carbon. We use the % change in social cost of carbon to suggest the additional GDP losses by 2050 relative to the baseline under their central estimate and the 10% tail probability. Effectively, we add the "additional social cost of carbon" as an additional drag on growth above the baseline by converting it into implied lower growth pathways.

While the social cost of carbon does not equate one to one to future GDP losses, it can be used as a proxy for long-term GDP effects assuming that the stream of undiscounted damages is flat or has a shape that equates to the % uplift in 2050. The second is the % increase in marginal damages is equal to the % increase in total damages. Finally, we concentrate here on the GDP impacts until 2050, which can also be contested.

The distribution of cash flows is not provided by Dietz et al., but given the assumptions above, this appears as an acceptable shorthand. While this may overstate the effects, it is worth flagging that review letters to the study suggest that it may even understate the shocks (see also Carbon Tracker Initiative 2023). While we recognize potential limitations to these assumptions, we consider them as a first order of magnitude relevant and appropriate. According to Dietz et al., the 2% tail probability is roughly double the 5% tail probability, so this demonstrates that even more extreme model runs are possible. This is also identified by other literature and analysis complementing that of Dietz et al. These tail probabilities may still understate outcomes when considering the additional ecosystem and biodiversity ramifications associated with the tipping points. While we use a global average, there are significant regional differences to the social cost of carbon which would with a more granular analysis provide more country-specific results (see Fig. below).

Fig 2.2: Country level impacts of climate tipping points (Source: Dietz et al. 2019)



Country-level expected SCC estimates (2020 US dollars) without tipping points (Upper) and the percentage change in the expected country-level SCC due to all tipping points (Lower). Welfare changes are normalized to global mean consumption per capita. Specification comprises RCP4.5-SSP2 emissions and GDP/population growth, Hope and Schaefer PCF, Whiteman et al. beta OMH, and IPSL AMOC hosing. Monte Carlo sample size is 10,000 with 0.1% trimmed.

- **Ecosystem tipping points:** Projections for ecosystem, where biodiversity plays a key part, losses are taken from WWF (2020) and World Bank (2021).[2] WWF estimates are more conservative than those from the World Bank, however the World Bank estimates only go out to 2030 with subsequent assumptions around a policy response. We assume here for consistency that the effects measured by the World Bank take longer to materialize and go out to 2050. This may be a more conservative assumption as to the time horizon of the risks, but allows for more consistent and comparable analysis.
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- **Social tipping points / Social conflicts (*Social*).** The second component are social risks or social climate tipping points. These relate to the impacts of climate change on social stability, political and social conflicts, as well as migration. We rely here on two different studies, one focused on a developed market (Northern Ireland Troubles, Dorsett 2019) and one global study from 2022 that demonstrates that over a 20-30 year period conflicts lower GDP by about 12% (de Groot et al. 2022). We take this figure as an end GDP shock and extrapolate linearly from today in terms of year on year negative GDP effects from social conflicts. This linear assumption may be contested as social conflicts may only escalate in the future and current levels of conflict may not translate to GDP effects. On the other hand, social conflicts may also escalate into more pronounced full out wars which may have more dramatic GDP effects.

These reference points are translated into financial shocks through a simple discount dividend model. The following briefly summarizes the key assumptions:

- The discount dividend model assumes a 1:1 relationship between long-term growth and long-term dividend profiles of companies (MSCI Barra 2010). We recognize that this relationship may not hold for a number of reasons and relies on a number of key assumptions and conditions, however, there is empirical evidence for the long-run relationship at least at global level. It should be noted that this also means the exercise is not a simulation of a 'repricing' event, but simply the shock in net present value to long-run equity returns in a "no impact" and "impact" scenario based on the different simulated GDP pathways;

- We use a 7% discount rate for future cash flows. Note, results are not very sensitive to reasonable adjustments to that assumption. The 7% discount rate is based on the US implied market return, based on the market risk premium and the risk free rate, derived from market-risk-premia.com on the 23rd of October, 2023..

- Our baseline growth path is based on projections from the Economist Intelligence Unit of 2.5% (2020-2030); 2% (2030-2040); 1.8% (2040-2050) for an average growth rate of ~2%.

- The discount dividend model is based on a 28 year cash flow profile until 2050 and a terminal value of 0%. The terminal value was fixed at 0% for simplicity reasons, but the choice does not materially effect the results given the discounted nature of the value in terms of net present value.

- The model compounds the risks, recognizing that they may be both mutually reinforcing but also materialize in a way where the sum is less than its parts. As we seek to look at the topic from a stress-test perspective, we think this approach is appropriate. This means concretely that we add the risks to each other and treat them as cumulative. This approach may hide the extent to which when both risks materialize at the same time they may "offset" or "double count" certain losses and the extent to which they may aggravate each other. Given the balance of uncertainties, we simply add them together, recognizing the caveats that come with this approach.

[2] Note the the paper has been re-released in an academic journal with some updated results and a different methdology. For the purpose of the exercise here we consider the original publication to be more easily integrated and given the overall limited differences in results, will rely on the original publication.

This note will focus on potential equity losses with subsequent research set to tackle a broader universe of assets.

Methodological deep-dive:

The model used in this paper is a multi-period discount dividend model where

$$P = \sum_{1}^{n} \left(\frac{D^n}{(1+r)^n} \right) + \frac{P^n}{(1+r)^n}$$

Where P is the share price, D the dividend payout at timer period n, and r the discount rate. The model limit for *n* is set to 28, assuming that the analysis is conducted between 2022-2050 where 2050=28. The model assumes no residual value, such that .

$$0 = \frac{P^{28}}{(1+r)^{28}}$$

The equity shocks are calculated by taking the difference in the baseline and the shocked scenario

$$L = -(1 - \frac{P_{shock}}{P_{baseline}})$$

Where *L* is the equity loss. The baseline dividends are estimated based on the PWC global growth projections

$$D_{baseline}^{n} = D_{baseline}^{n-1} * (1 + g_{baseline})$$

Where values for r are summarized below. For simplicity, $D_{baseline}^{0}$ is indexed to 100.

Time interval for $g_{baseline}$	Growth rate
$g_{baseline}$ (2022-2030)	2.5%
$g_{baseline}$ (2031-2040)	2%
$g_{baseline}$ (2041-2050)	1.8%

The shock dividends are estimated

$$D_{shock}^{n} = D_{shock}^{n-1} * (1 + g_{shock})$$

For simplicity, D_{shock}^{0} is indexed to 100 and

$$g_{shock} = (\frac{(GDP_{baseline}^{28} * (1+s))}{GDP_{baseline}^{0}})^{1/28} - 1$$

Where s is derived from the literature and represents the percentage GDP reduction in 2050 (n=28) based on the following table

Shock s	1in1000 Scenario (“High Baseline)	SwissRe Scenario (“Low Baseline”)
Baseline GDP loss from climate change	-18.0%	-5.7%
Tipping point - Central	-7.6%	-2.4%
Tipping Point - 10% outlier	-10.4%	-3.3%
Ecosystem loss – WWF	-0.6%	-0.6%
Ecosystem loss – WorldBank	-2.3%	-2.3%
Social risks (Dorset 2019, de Groot et al. 2022)	-12.0%	-12.0%

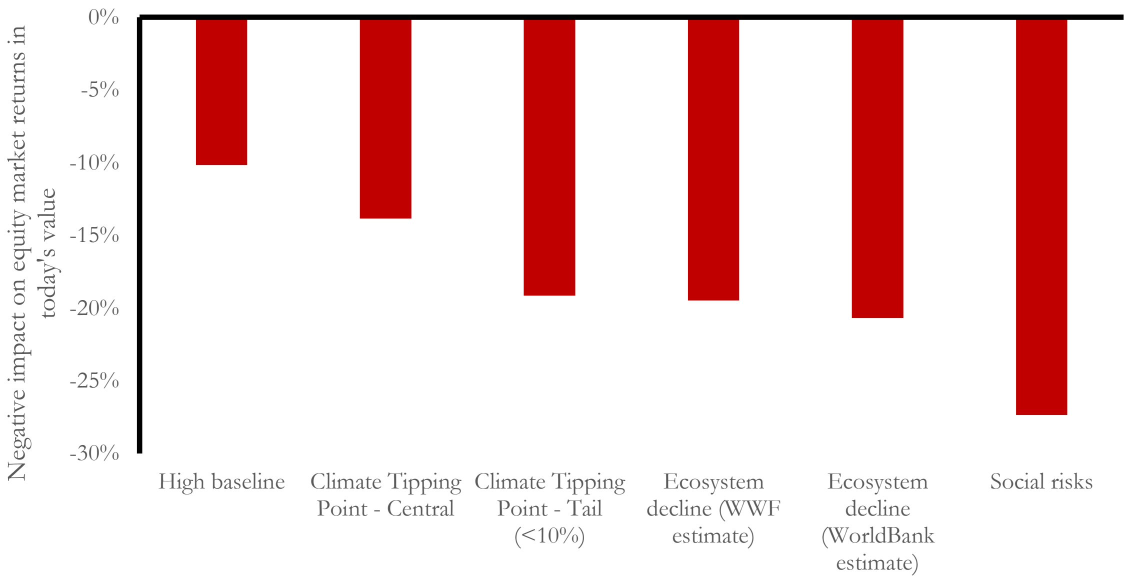
III. Results

Social and ecosystem risks have the potential to amplify the financial losses in equity markets from climate change by a factor of 2.5-3.5x.

Integrating ecosystem changes related to climate tipping and social conflicts related to global warming amplifies losses both under a low baseline climate losses scenario and a 'high' baseline as per the 2DII stress-test scenario from 2019. These losses are dramatic as they are secular and not cyclical, in other words they represent permanent value destruction. It is worth flagging that this event would be unprecedented in modern financial market history. The figures below summarize the results using the SwissRe baseline and 2DII baseline reference points for losses.

As outlined above, these are not losses based on a 'repricing' assumption given the uncertainty around current market pricing of these risks, risk premia effects, and sentiment impacts, but rather the impacts in terms of expected equity market returns under a baseline "no impact" and "impact scenario.

Fig 3.1: Reduction in global equity market returns and GDP growth rates under a 1in1000 "high" baseline (Source: Authors, based on Dietz et al. 2019, de Groot et al. 2022, SwissRe 2021, WWF 2020, World Bank 2021, 2DII 2019)



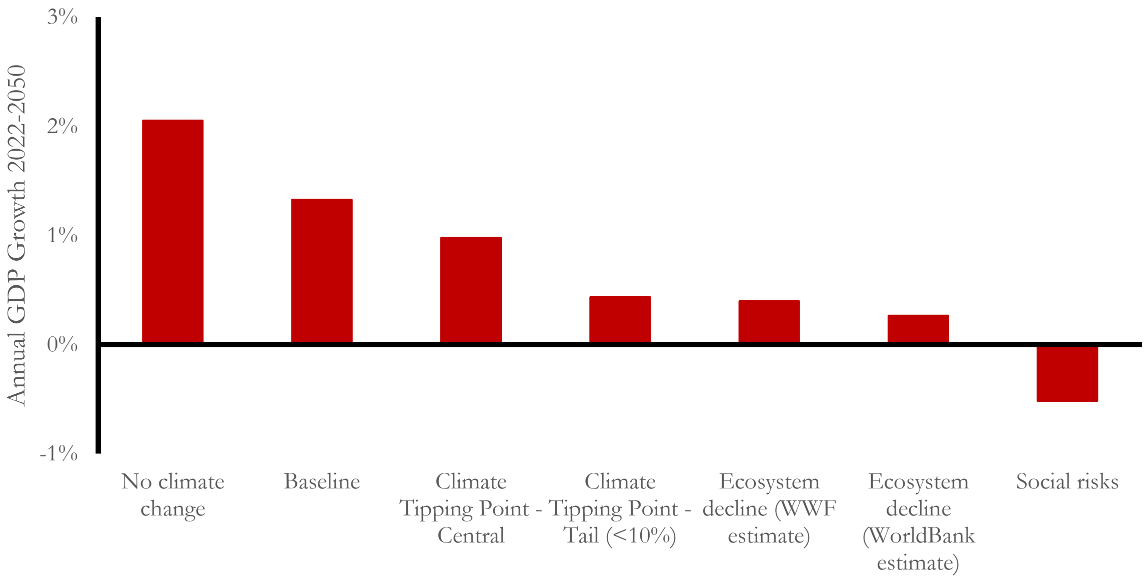
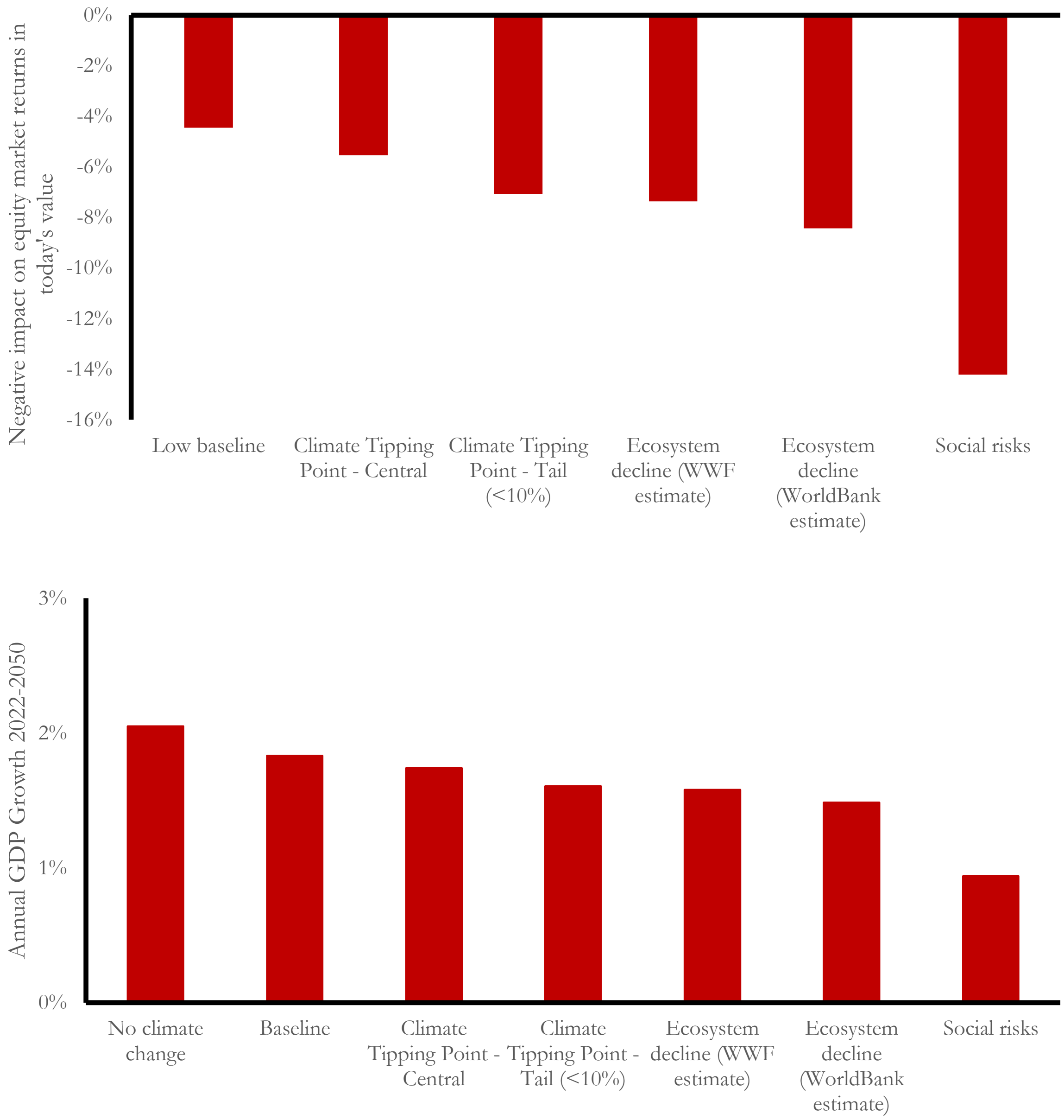


Fig 3.2: Reduction in global equity market returns and GDP growth rates under a SwissRe "low" baseline (Source: Authors, based on Dietz et al. 2019, de Groot et al. 2022, SwissRe 2021, WWF 2020, World Bank 2021)



Translating these losses into absolute values, potential social and ecosystem feedback loops can wipe $31 trillion from global capital markets in terms of lower returns.

These findings do not draw specific inferences about financial stability but demonstrate the important relationship between climate change and social and ecosystem considerations. Estimates around global equity losses are based on a total estimated equity market size of $117 trillion (SIFMA 2022).

It is important to highlight that these losses are 'stress-test scenarios' and not central estimates or forecasts.

The paper does not comment on the probability of these losses materializing to capital markets or the individual events happening in the way they are calibrated in this paper. Rather, they are designed to demonstrate that the current suite of 'physical risk' scenario analysis and climate stress-tests do not in fact stress the full range of system stressors the economic and financial system faces under extreme climate change over the next 30 years.

It is hard to understand what a radically different world these scenarios represent, with the most extreme case leading to what is effectively a permanent global economic recession.

The average growth rate under the most extreme scenario presented here (2DII baseline + 10% tipping point outcome + social conflict) equates to an average annual growth rate of -0.3% over the next 30 years. Such outcomes are truly unprecedented – effectively a permanent recession. This dynamic may be unevenly distributed with periods of positive and negative growth, but leads to a truly different world.

The ramifications of long-term negative growth are unprecedented in modern economic history and will likely have dramatic effects for all asset classes. Real estate prices in particular correlate significantly with GDP per capita (Tripathi 2019). While these effects are not explored in this paper, they suggest the potential for a profound long-term economic and financial transformation that creates risks to financial markets currently not mapped by standard stress-test and scenario analysis exercises.

IV. Conclusion

This report represents the first attempt to bring together the potential financial risks that come from tail scenarios linking climate, ecosystem, and social risks.

The findings suggest that losses from physical risks may be a factor of 2.5-3.5 higher as a result of these broader dynamics triggered by climate change and creating feedback loops in terms of financial losses. It is worth highlighting again however the extent to which these findings are not central estimates but potential tail losses to be considered under extreme climate change scenarios.

The exercise represents a basic modelling approach to highlight the sensitivities and potential orders of magnitude of different effects based on a basic valuation model.

There are obviously a host of limitations to the analysis conducted here, notably the extent to which GDP effects translate directly into valuation effects, the extent to which some of these risks may already be priced, the lack of consideration of sectoral exposures and potential adaptation (Kahn et al. 2021), and the focus on equity markets only. There are also other limitations which relate to the actual accuracy of the analysis, notably the uncertainty as to the timing of climate tipping point risks materializing, and the overall uncertainty around the interplay between climate tipping points, ecosystem decline, and social conflicts / tipping points. The results here are thus first approximations and heuristics designed for stress-tests and not 'base case' or 'forecast' estimations.

Given the limitations of this exercise, 1in1000 will seek to build on the analysis provided here to develop more sophisticated and detailed climate stress-tests moving forward.

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