Response: Clarifying the Failure Rate of Loans Mechanism in FRIDA

By: William Schoenberg

Thank you for this constructive exchange. I believe the remaining disagreement can be broached by a clarification of what the failure rate of loans (FRoL) mechanism represents in FRIDA and, consequently, how the historical divergence between the FRoL and NoImpacts trajectories should be interpreted.

You summarize FRIDA as resting on three assumptions: (i) that SSP-like trajectories provide the appropriate no-climate-damages counterfactual, (ii) that historical differences between those trajectories and observed economic development are explained by climate damages, and (iii) that the calibration therefore assigns a dominant role to the banking channel. We agree that these are important issues. However, this interpretation of the FRoL mechanism differs substantially from the mechanism we have implemented in FRIDA.

1. Clarifying the role of SSPs and the no-damages trajectory

Before addressing the financial transmission mechanism itself, it may be helpful to clarify how the NoImpacts trajectory is constructed and how SSP scenarios are used in our analysis. A central concern in your comment appears to be the interpretation of the NoImpacts scenario as an externally imposed estimate of a no-climate-damages counterfactual. This is not how FRIDA is calibrated or used. FRIDA is calibrated exclusively to historical observations. SSP trajectories are never used as calibration targets, nor are they imposed as assumptions about how the global economy would have evolved in the absence of climate change. The NoImpacts trajectory emerges endogenously from the calibrated model by removing climate-related damages while leaving the remaining model structure unchanged. It is therefore a model result, not a calibration input. The relevance of the SSP comparison is considerably more limited and was initially raised in response to your original review. In your most recent comment, the concern appears to be that the economic growth implied by the NoImpacts trajectory is implausibly strong. To evaluate that concern, Figure 1 below compares FRIDA projections with the range of GDP per capita trajectories represented by the SSP literature.

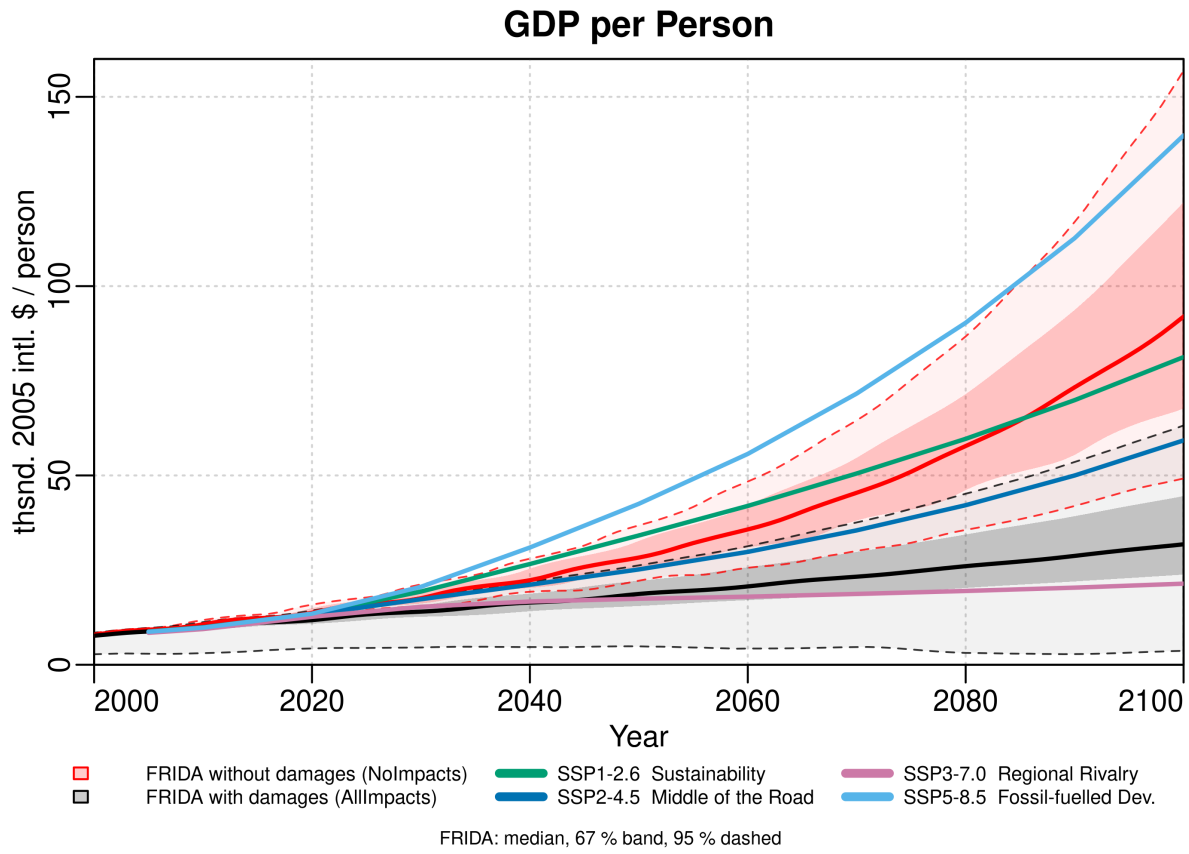

Figure 1. GDP per capita trajectories from FRIDA compared with illustrative SSP-baseline projections. FRIDA is calibrated solely to historical observations. The NoImpacts trajectory emerges endogenously from the calibrated model and is shown alongside SSP trajectories only as an external benchmark.

I have produced this comparison for you to demonstrate that the growth trajectory implied by the NoImpacts simulation falls within the range of long-run socioeconomic futures commonly considered plausible in the scenario literature which also generally does not include climate impacts. The comparison is thus presented as a consistency check on model behavior, not as evidence used for calibration.

More generally, and I think this is at the heart of what I believe to be the misunderstanding, FRIDA is a growth-damage model. Small differences in investment, innovation, and productivity growth accumulate over time creating path-dependencies, producing increasingly divergent development trajectories. Consequently, substantial differences in GDP per capita levels by the end of the simulation period do not imply equally large contemporaneous annual damages. They reflect the cumulative consequences of persistent differences in growth rates over many decades.

2. FRoL does not represent banks pricing physical climate risk into lending decisions

Your observation that much lending prior to 2020 did not explicitly incorporate physical climate risk is entirely reasonable. However, this is precisely the situation represented by FRIDA.

The FRoL channel does not assume:

> climate-risk recognition → climate-adjusted lending standards → lower GDP

Instead, it represents:

> climate damages → business and household financial distress → increased loan and investment failures → tighter credit conditions → lower investment and innovation → slower economic growth → lower GDP overtime

In FRIDA, climate-related shocks increase the failure rate of loans and investments (Wells et al., 2025). Banks then respond to these realized defaults through standard credit-risk management behavior by tightening lending standards. This reduces credit availability, investment, innovation, and ultimately economic growth (Grimeland et al., 2026). The mechanism operates regardless of whether banks correctly identified, quantified, or priced climate risks beforehand. Indeed, the fact that physical climate risk was often under-priced historically is entirely consistent with this framework. The economy module explicitly describes how higher default rates induce tighter lending standards, reducing credit creation and investment through well-established financial feedbacks.

This distinction is critical to our modeling. The mechanism represents climate-unaware, but vulnerable borrowers, investments, and assets, not climate-aware lenders. As implemented in FRIDA, higher default rates induce tighter lending standards, reducing credit creation and investment activity (Grimeland et al., 2026). This is consistent with a substantial literature showing that observed defaults lead banks to tighten lending standards and reduce credit creation (e.g., Dell'Ariccia and Marquez, 2006; Fishman et al., 2024; Rodano et al., 2018). More fundamentally, the FRoL mechanism is motivated by a broader concern that many optimizing integrated assessment models implicitly assume climate damages can be anticipated and absorbed without materially affecting the functioning of financial markets.

Standard damage-function approaches generally represent climate change as a reduction in productive output while leaving the financial system's ability to allocate capital largely unaffected. In contrast, FRIDA explicitly explores the possibility that climate change

increases the failure rate of loans and investments, thereby altering future lending, i.e., investment behavior, and credit creation, which impacts indirectly innovation, and ultimately economic growth. Under this interpretation, climate-related defaults are not merely accounting losses i.e. contemporaneous annual damages. They become part of an endogenous feedback that influences the financial system's capacity to mobilize resources over time.

This perspective is consistent with a growing literature arguing that finance, credit creation, financial instability, and uncertainty remain underrepresented in many climate-economy modeling frameworks (Chenet et al., 2021; Espagne, 2018; Stern et al., 2022). Researchers have repeatedly highlighted the need for stronger representation of financial mechanisms, credit constraints, and investment dynamics within integrated assessment models because these mechanisms may materially influence long-run economic trajectories (Battiston et al., 2021; Lamperti et al., 2019; Monasterolo, 2020).

The FRoL experiment should therefore be interpreted as an exploration of one possible climate-financial transmission mechanism rather than an assertion that banks historically priced physical climate risk correctly or explicitly incorporated climate risk assessments into lending decisions. The mechanism operates even when climate risks are poorly understood or systematically under-priced because it is driven by realized defaults rather than ex ante risk recognition.

I therefore believe there is an important distinction between your observation and the interpretation you draw from it. Your experience that financial institutions did not explicitly incorporate physical climate risk into lending decisions historically is not evidence against the FRoL impact channel. If climate risks were systematically under-priced, one would still expect climate-related shocks to generate bankruptcies, defaults, loan losses, and balance-sheet impairments once those risks materialize.

In other words, FRIDA does not require:

> banks understand climate risk

It requires only:

> climate impacts damage borrowers, investments, infrastructure, or assets, resulting in higher default rates.

The subsequent raising of lending standards emerges as a standard response of the financial system to deteriorating loan performance. The mechanism therefore remains operative regardless of whether climate risk was recognized beforehand.

3. There is substantial empirical evidence that climate-related shocks generate financial losses

I respectfully disagree with the suggestion that there is little evidence linking climate-related shocks to bankruptcies, loan losses, or broader financial distress.

The question is not whether climate change causes financial failures. The evidence on this point is substantial.

For example, [future] US Senator Elizabeth Warren (2005) at the Boston Branch of the US federal reserve, discusses empirical research by Lawless (2005), who reports that bankruptcy filing growth rates were approximately 50% higher in US states directly affected by major hurricanes during the three years following landfall.

Historical examples point in the same direction:

- Hurricane Andrew contributed to the insolvency of at least sixteen insurance companies and fundamentally reshaped Florida insurance markets (Insurance Information Institute, 2026). Also more generally how increased hurricane activity in the Caribbean has limited credit availability (Brei et al., 2019).
- Climate-related wildfire liabilities were a major contributor to the PG&E bankruptcy (Balaraman, 2020; Gold, 2019).
- Mortgage-market studies increasingly link physical climate risks to higher delinquency rates, foreclosure rates, and lender losses (First Street, 2025; Moody's Analytics, 2021; O'Rourke et al., 2024).
- Recent IMF work finds that climate-disaster losses increase sovereign default risk (de Soyres et al., 2026).

These examples do not establish the exact magnitude of global climate damages. However, they provide strong evidence that climate-related shocks generate loan losses, bankruptcies, insurer failures, economic distress, and broader forms of financial instability that propagate beyond the directly affected sectors.

Beyond disaster case studies, a growing body of finance literature supports the plausibility of the transmission pathway represented by FRoL. Recent work has linked climate exposure to elevated bankruptcy risk, increased financial fragility, and heightened credit risk (Capasso et al., 2020; Feng et al., 2024; Klomp, 2014; Noth and Schüwer, 2023). Studies of lending standards and non-performing loans consistently find that rising defaults induce tighter lending conditions, reduced credit creation, and lower investment activity (Accornero et al., 2017; Chiesa and Mansilla-Fernández, 2021; Cucinelli, 2015). The banking response itself is therefore well established in the literature (Blickle et al.,

2026; Nie et al., 2023). Therefore, I don't think we need to ask whether defaults lead to tighter credit conditions, and reduced investment, but instead to what extent climate change contributes to those defaults.

Similarly, evidence is accumulating that climate change can affect banking-sector stability and asset quality directly (Brei et al., 2019; Klomp, 2014; Nie et al., 2023; Noth and Schüwer, 2023). Research examining the exposure of financial institutions to climate-related physical risks increasingly finds that climate-sensitive assets may create vulnerabilities that extend beyond the immediately affected firms or regions (Barrot and Sauvagnat, 2016; Cortés and Strahan, 2017; Mandel et al., 2025; Rehbein and Ongena, 2022).

4. Growth effects, vs. contemporaneous annual damages

I believe this is the central issue underlying the remaining disagreement.

The approximately 10% historical divergence between FRoL and NoImpacts should not be interpreted as an estimate that climate-related changes in lending standards reduced global GDP by 10% in 2020 without considering the previous 40 years of path-dependency.

FRIDA is structurally a growth-damage model, not a level-damage model. Climate-related financial stress affects investment, innovation, productivity growth, and capital formation. The interpretation is not annual damages but cumulative differences in growth trajectories accumulated over the time period over which the damages are simulated.

This logic is consistent with a large macro-financial literature showing that financial crises can produce persistent reductions in potential output and long-run growth rather than merely temporary declines in GDP. Research by Furceri and Mourougane (2012) and Reinhart and Reinhart (2015), among others, finds that financial disruptions often leave long-lasting effects on economic growth trajectories. FRIDA applies this same intuition to climate-driven financial stress.

Consequently, the divergence between FRoL and NoImpacts does not imply that one should observe a contemporaneous, annual, 10% GDP loss attributable to climate-related lending responses. Rather, it reflects the cumulative difference between:

1. an economy experiencing repeated, small at the global level, climate-related financial losses that propagate through investment and innovation dynamics; and
2. a counterfactual economy in which those climate-related losses never occurred, and therefore never propagated and compounded in the first place.

Even relatively small changes in annual growth rates can accumulate into large differences in absolute levels over multiple decades.

5. Conclusions

I fully agree that the magnitude of this mechanism remains uncertain and deserves further empirical investigation. I also agree that improved empirical constraints on climate-related loan failures, default rates, and financial adaptation responses would be highly valuable.

However, I respectfully disagree with the characterization that FRIDA assumes widespread historical climate-risk pricing by banks, or that the FRoL mechanism lacks empirical grounding. Rather, FRIDA explores the hypothesis that climate-driven financial failures themselves may constitute an important amplification pathway. This hypothesis is motivated by both theory and evidence: theory highlighting the potential importance of financial-sector dynamics for long-run economic development, and empirical evidence showing that climate-related shocks can generate defaults, bankruptcies, insurer failures, mortgage distress, sovereign financial stress, and other forms of financial disruption.

In my view, the relevant scientific question is therefore not whether climate-related financial transmission mechanisms exist, but rather how strongly climate-induced defaults, bankruptcies, and financial distress propagate through investment, innovation, productivity, and long-run economic growth. FRIDA is intended as an explicit exploration of that question and via FRIDA's large uncertainty ensemble we explore a large range of impact magnitudes associated with the FRoL climate damage pathway.

6. References

Accornero, M., Carpinelli, L., and Sorrentino, A. M.: Non-Performing Loans and the Supply of Bank Credit: Evidence from Italy, SSRN Journal, https://doi.org/10.2139/ssrn.2954995, 2017.

Balaraman, K.: Wildfires pushed PG&E into bankruptcy. Should other utilities be worried?, , Utility Dive19th November, 2020.

Barrot, J.-N. and Sauvagnat, J.: Input Specificity and the Propagation of Idiosyncratic Shocks in Production Networks*, The Quarterly Journal of Economics, 131, 1543–1592, https://doi.org/10.1093/qje/qjw018, 2016.

Battiston, S., Monasterolo, I., Riahi, K., and Van Ruijven, B. J.: Accounting for finance is key for climate mitigation pathways, Science, 372, 918–920, https://doi.org/10.1126/science.abf3877, 2021.

Blickle, K. S., Hamerling, S. N., and Morgan, D. P.: How Bad Are Weather Disasters for Banks?, J of Money Credit Banking, jmcb.70036, https://doi.org/10.1111/jmcb.70036, 2026.

Brei, M., Mohan, P., and Strobl, E.: The impact of natural disasters on the banking sector: Evidence from hurricane strikes in the Caribbean, The Quarterly Review of Economics and Finance, 72, 232–239, https://doi.org/10.1016/j.qref.2018.12.004, 2019.

Capasso, G., Gianfrate, G., and Spinelli, M.: Climate change and credit risk, Journal of Cleaner Production, 266, 121634, https://doi.org/10.1016/j.jclepro.2020.121634, 2020.

Chenet, H., Ryan-Collins, J., and Van Lerven, F.: Finance, climate-change and radical uncertainty: Towards a precautionary approach to financial policy, Ecological Economics, 183, 106957, https://doi.org/10.1016/j.ecolecon.2021.106957, 2021.

Chiesa, G. and Mansilla-Fernández, J. M.: The dynamic effects of non-performing loans on banks' cost of capital and lending supply in the Eurozone, Empirica, 48, 397–427, https://doi.org/10.1007/s10663-020-09475-5, 2021.

Cortés, K. R. and Strahan, P. E.: Tracing out capital flows: How financially integrated banks respond to natural disasters, Journal of Financial Economics, 125, 182–199, https://doi.org/10.1016/j.jfineco.2017.04.011, 2017.

Cucinelli, D.: The Impact of Non-performing Loans on Bank Lending Behavior: Evidence from the Italian Banking Sector, EJBE, 8, 59–71, https://doi.org/10.17015/ejbe.2015.016.04, 2015.

Dell'Ariccia, G. and Marquez, R.: Lending Booms and Lending Standards, The Journal of Finance, 61, 2511–2546, https://doi.org/10.1111/j.1540-6261.2006.01065.x, 2006.

Espagne, E.: Money, Finance and Climate: The Elusive Quest for a Truly Integrated Assessment Model, Comp Econ Stud, 60, 131–143, https://doi.org/10.1057/s41294-018-0055-7, 2018.

Feng, F., Han, L., Jin, J., and Li, Y.: Climate Change Exposure and Bankruptcy Risk, British J of Management, 35, 1843–1866, https://doi.org/10.1111/1467-8551.12792, 2024.

First Street: Climate as the Sixth "C" of Credit: Scientific Evidence that Climate Risk Now Drives Mortgage Foreclosure and Loan Viability, https://firststreet.org/press/climate-as-the-sixth-c-of-credit-scientific-evidence-that-climate-risk-now-drives-mortgage-foreclosure-and-loan-viability, last access: 24 August 2026, 2025., 2025.

Fishman, M. J., Parker, J. A., and Straub, L.: A Dynamic Theory of Lending Standards, The Review of Financial Studies, 37, 2355–2402, https://doi.org/10.1093/rfs/hhae010, 2024.

Furceri, D. and Mourougane, A.: The effect of financial crises on potential output: New empirical evidence from OECD countries, Journal of Macroeconomics, 34, 822–832, https://doi.org/10.1016/j.jmacro.2012.05.010, 2012.

Gold, R.: PG&E: The First Climate-Change Bankruptcy, Probably Not the Last, , Wall Street Journal18th January, 2019.

Grimeland, M. B., Blanz, B., Schoenberg, W., and Callegari, B.: Schumpeterian disaggregation and integrated assessment: An endogenous, stock-flow consistent economy in disequilibrium for FRIDA v2.1, https://doi.org/10.5194/egusphere-2025-6342, 3 February 2026., 2026.

Insurance Information Institute: Hurricane Andrew Fact Sheet, https://www.iii.org/article/hurricane-andrew-fact-sheet, last access: 24 August 2026, 2026., 2026.

Klomp, J.: Financial fragility and natural disasters: An empirical analysis, Journal of Financial Stability, 13, 180–192, https://doi.org/10.1016/j.jfs.2014.06.001, 2014.

Lamperti, F., Bosetti, V., Roventini, A., and Tavoni, M.: The public costs of climate-induced financial instability, Nat. Clim. Chang., 9, 829–833, https://doi.org/10.1038/s41558-019-0607-5, 2019.

Lawless, R. M.: Bankruptcy filing rates after a major hurricane, Nev. LJ, 6, 7, 2005.

Mandel, A., Battiston, S., and Monasterolo, I.: Mapping global financial risks under climate change, Nat. Clim. Chang., 15, 329–334, https://doi.org/10.1038/s41558-025-02244-x, 2025.

Monasterolo, I.: Climate Change and the Financial System, Annu. Rev. Resour. Econ., 12, 299–320, https://doi.org/10.1146/annurev-resource-110119-031134, 2020.

Moody's Analytics: The storm ahead for mortgage default models, https://www.moodys.com/web/en/us/insights/credit-risk/the-storm-ahead-for-mortgage-default-models.html, last access: 24 August 2026, 2021., 2021.

Nie, O., Regelink, M., and Wang, D.: Banking Sector Risk in the Aftermath of Climate Change and Environmental-Related Natural Disasters, Policy Research Working Paper, World Bank, Washington, DC, https://documents.worldbank.org/curated/en/099548302222320303 (last access: 24 August 2026), 2023.

Noth, F. and Schüwer, U.: Natural disasters and bank stability: Evidence from the U.S. financial system, Journal of Environmental Economics and Management, 119, 102792, https://doi.org/10.1016/j.jeem.2023.102792, 2023.

O'Rourke, C., Devries, P., Sheffield, J., Kodra, E., and Hay, C.: Mortgage delinquencies and climate risk: The tail risks of agency credit risk transfer pools, https://www.ice.com/insights/sustainable-finance/mortgage-delinquencies-and-climate-risk, last access: 24 August 2026, 2024., 2024.

Rehbein, O. and Ongena, S.: Flooded Through the Back Door: The Role of Bank Capital in Local Shock Spillovers, J. Financ. Quant. Anal., 57, 2627–2658, https://doi.org/10.1017/S0022109022000321, 2022.

Reinhart, C. M. and Reinhart, V. R.: Financial Crises, Development, and Growth: A Long-term Perspective, World Bank Econ Rev, 29, S53–S76, https://doi.org/10.1093/wber/lhv011, 2015.

Rodano, G., Serrano-Velarde, N., and Tarantino, E.: Lending Standards over the Credit Cycle, The Review of Financial Studies, 31, 2943–2982, https://doi.org/10.1093/rfs/hhy023, 2018.

de Soyres, C., Obeng, E., and Tan, J.: Climate Shocks, Debt Defaults and Investment in Climate Adaptation - Squaring an Impossible Trilemma, IMF Working Papers, International Monetary Fund, Washington, DC, https://www.imf.org/-/media/files/publications/wp/2026/english/wpiea2026128-source-pdf.pdf (last access: 24 August 2026), 2026.

Stern, N., Stiglitz, J., and Taylor, C.: The economics of immense risk, urgent action and radical change: towards new approaches to the economics of climate change, Journal of Economic Methodology, 29, 181–216, https://doi.org/10.1080/1350178X.2022.2040740, 2022.

Warren, E.: natural disasters and bankruptcy, https://www.bostonfed.org/-/media/Documents/cb/PDF/disaster.pdf, 2005.

Wells, C., Blanz, B., Ramme, L., Breier, J., Callegari, B., Muralidhar, A., Rajah, J. K., Lindqvist, A. N., Eriksson, A. E., Schoenberg, W. A., Köberle, A. C., Wang-Erlandsson, L., Mauritzen, C., and Smith, C.: The Representation of Climate Impacts in the FRIDAv2.1 Integrated Assessment Model, https://doi.org/10.5194/egusphere-2025-2756, 14 July 2025., 2025.