

From accelerating growth to biophysical brakes: The processes that shape the future of the global human & Earth System

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Abstract

An unresolved challenge in climate science is to understand how long-term interactions among macroeconomic processes, population dynamics, energy systems, land use, and climate physics shape the co-evolution of the fully coupled human and Earth system. By systematically exploring the feedback processes in a fully coupled human and Earth system model, we illustrate how the global economy transitions from growth-reinforcing dynamics in the 20th century to climate-impact-balancing dynamics in the 21st and early 22nd centuries. The Earth system constraints arise gradually through the turbulent joining of economic, financial, and environmental processes. Our results suggest that technological progress and natural behavioral adaptation are insufficient to offset accumulating climate damages; instead, early feedback-targeted policy interventions are essential to avoid futures where climate impacts determine global development trajectories. This work demonstrates the importance of feedback-centric modeling for understanding planetary change.

1. Introduction

The consequences of climate change increasingly shape global development pathways, fundamentally influencing human wellbeing. Humans and the Earth system are connected through a myriad of feedback processes, many of which are undergoing significant change as the climate evolves (Burke et al., 2015; Donges et al., 2021; Moore et al., 2022; Rennert et al., 2022). In this frame, climate impacts are integral components of the feedback structures governing the co-evolution of the coupled human–Earth system. Understanding how these feedback processes change, and how they interact to produce system-level behavior, is essential for assessing plausible futures that may unfold over the coming century and beyond (Tebaldi et al., 2026). As climate change accelerates and its societal impacts intensify, a central challenge is to identify the key feedback processes that have produced current risks and those likely to shape future trajectories. Repeated calls have therefore been made for deeper connections between human and Earth system components in integrated modelling (Baldos et al., 2023; Beckage et al., 2020; Otto et al., 2020; Rising et al., 2022; Robinson et al., 2018).

Historically, Integrated Assessment Models (IAMs) have been developed to study this class of problem, drawing on a wide range of climate-damage functions to represent impacts of climate change on human systems. However, these implementations typically address sectoral pathways in relative isolation – for example, using aggregate macroeconomic loss functions, agricultural yield responses, or energy-demand sensitivities (Awais et al., 2024; Diaz, 2016; Hartin et al., 2021; Orlov et al., 2024; Van Ruijven et al., 2019). While these approaches have advanced understanding of climate risks, they provide limited insight into how interactions among multiple sectors combine to shape the long-term evolution of coupled human and Earth systems. In particular, they often provide less visibility into the feedback structures through which climate impacts propagate across economic, demographic, technological, and environmental domains (Rising et al., 2022). This leaves an important scientific question unresolved: how do interactions among macroeconomic processes, population dynamics, energy systems, land use,

and climate physics collectively shape the long-term co-evolution of the human-Earth system, and how does the importance of different feedback processes change over time?

Addressing this question requires modelling approaches that explicitly represent the dynamic interactions and feedback loops between human and natural systems (Folke, 2006; Liu et al., 2007). In recent years, several authors have argued that understanding climate change requires moving beyond one-way impact assessments toward fully coupled representations of climate-society co-evolution (Beckage et al., 2020; Moore et al., 2022; Otto et al., 2020). Such approaches enable researchers not only to estimate future outcomes, but also to identify the mechanisms through which those outcomes emerge. Understanding these mechanisms is particularly important because climate change unfolds over long time horizons in systems characterized by delays, nonlinearities, adaptation, and path dependence. Consequently, similar aggregate outcomes may arise from very different underlying processes, while seemingly small changes in feedback structures can produce substantial differences in long-run trajectories.

In this study, we use FRIDAv2.1, a fully coupled global integrated assessment model that explicitly links Earth system processes with population dynamics, economics, agriculture, finance, and energy systems (Schoenberg et al., 2025). FRIDA closes key two-way feedback loops between socio-economic activity and biophysical climate dynamics, enabling endogenous human-Earth co-evolution creating trajectories that emerge from internally represented processes such as: expectation formation (Schoenberg and Callegari, 2025), investment dynamics (Grimeland et al., 2026), behavioral adaptation (Rajah et al., 2025), climate dynamics (Wells et al., 2026a), sea level rise (Ramme et al., 2025), and climate impacts on productivity, mortality, infrastructure, and resource availability (Wells et al., 2026b). Rather than relying on externally specified growth pathways, the model represents human systems as adaptive and path-dependent, allowing climate damages to directly alter economic development, population dynamics, and demand for energy and land-based goods (Schoenberg et al., 2025; Wells et al., 2026b).

The objective of this paper is to identify the feedback processes that govern the long-term co-evolution of the coupled human-Earth system and to examine how the dominance of these processes changes as climate impacts accumulate. Specifically, we address three research questions:

1. Which feedback processes dominate system behaviour across the evolution of the coupled human-Earth system?
2. How do transitions in feedback dominance emerge as climate impacts intensify over time?
3. Through which mechanisms do climate impacts influence long-term economic, demographic, energy-system, and land-use trajectories?

2. Methods

The analysis is based on a previously generated 100,000-member endogenous model behaviour (EMB) ensemble of FRIDA v2.1 spanning the period 1980-2150 (Schoenberg et al., 2025). Across the ensemble,

uncertainty is sampled throughout the major model domains, producing a wide range of possible climate and socioeconomic futures. Because the objective of this study is to identify the dominant feedback processes governing system behaviour rather than to characterize the statistical properties of the full ensemble, we reduce the analysis to a smaller set of representative simulations. These representative members are selected using the ensemble's distribution of surface temperature anomaly (STA). The full range is divided into eleven equal segments and the midpoint of each segment is used as a target quantile. For each target quantile, the simulation whose STA trajectory most closely matches that quantile over the full simulation horizon is selected. This procedure yields eleven representative simulations spanning the range of behaviour present in the entire ensemble, with the sixth member approximately corresponding to the ensemble median.

To identify the feedback processes responsible for model behaviour, we employ the Loops that Matter (LTM) method (Schoenberg et al., 2020, 2023). LTM is a quantitative feedback loop dominance analysis technique that determines the contribution of feedback loops to system behaviour throughout a simulation run. The method is based on the link score, which quantifies the influence of one model variable on another at a given point in time. Link scores are multiplied to calculate loop scores, providing a quantitative measure of the strength and polarity of individual feedback loops. Evaluating loop scores through time allows the changing importance of feedback structures to be tracked and periods of loop dominance to be identified objectively.

A practical challenge is that FRIDA contains a very large number of feedback loops, on the order of billions. To make the analysis tractable, we apply the Strongest Path Algorithm (SPA) (Eberlein and Schoenberg, 2020), which identifies the causal pathways with the largest multiplicative link scores while pruning weaker alternatives. Rather than exhaustively enumerating all loops in the model, SPA efficiently identifies those most influential for observed behaviour. Following application of SPA, the LTM implementation embedded within Stella Architect generates time series describing the importance of the dominant feedback loops throughout each simulation. These outputs provide the basis for all subsequent analysis.

Quantitative loop dominance analysis identifies which feedback loops are influential and when transitions in dominance occur, but additional interpretation is necessary to explain why these transitions arise. Following the structured feedback-analysis approach described by Rajah et al. (2026), we therefore construct feedback narratives for each representative simulation. For every representative sample run, the outputs of the LTM analysis are converted into a structured representation containing the constituent links of each influential feedback loop, loop polarity, and the complete time series of loop importance. These structured outputs are then transformed into narrative descriptions of system behavior using the ltm-narrative workflow, a generative AI tool based on Seldon (Schoenberg, 2026). The workflow is constrained by explicit model context and quantitative LTM outputs, limiting its role to translating structured information into prose rather than generating new analytical content.

The resulting eleven feedback narratives are subsequently synthesized into a single integrated description of ensemble dynamics. This synthesis focuses on identifying feedback processes that recur across simulations, common transitions in feedback dominance, differences among simulations that explain variation in outcomes, and the overall sequence of dominant processes governing coupled human-Earth system evolution. The integrated narrative provides the basis for the feedback structures and interpretations presented in the Results section.

To increase confidence in the analysis, validation was conducted at multiple stages. First, the narrative-generation workflow was applied to models with established feedback explanations to assess consistency between generated and known narratives. Second, subsets of FRIDA simulations were independently reviewed by the first and second authors, who compared generated narratives directly with the underlying loop-dominance results. Third, the synthesis procedure was evaluated by comparing synthesized narratives with the source narratives from which they were derived. Finally, the integrated interpretation was checked against targeted model experiments to verify that the feedback processes identified by the analysis were consistent with observed model behaviour. Throughout the study, the generated narratives informed but did not replace expert interpretation of the model and its dynamics.

3. Results

The results are presented in two stages. First, we examine the behaviour of the eleven representative simulations relative to the full 100,000-member endogenous model behaviour (EMB) ensemble. This establishes that the selected simulations span the range of futures generated by FRIDA. Second, we use feedback loop dominance analysis to identify the feedback processes responsible for the observed trajectories and how their relative importance changes through time. Across the ensemble, a consistent sequence of feedback regimes emerges despite substantial uncertainty in climate and socioeconomic outcomes. The dominant dynamics evolve from a growth-oriented regime driven primarily by reinforcing economic feedbacks, to a transition regime characterized by increasing interaction between economic and biophysical processes, and finally to a climate-constrained regime in which climate impacts become major determinants of system behaviour.

Figure 1 shows the eleven representative simulations superimposed on the full EMB ensemble. The selected simulations reproduce the range of future outcomes generated by the ensemble across key variables, including global temperature, economic output, population, employment, wages, food production, and energy-system development. Surface temperature anomaly spans a range from approximately 2-6°C in 2150 across the selected runs, with corresponding divergence in economic and demographic outcomes. While some trajectories maintain continued economic growth throughout the simulation period, others exhibit pronounced slowdowns or contractions as climate impacts accumulate. These differences provide the basis for examining how variations in feedback dominance produce different development pathways.

The late 20th century to the mid 21st century

The simulation begins in 1980, when warming since pre-industrial times is under half a degree Celsius, and it appears that climate change has relatively limited influence on the global human system. Across all 11 simulation runs of the reduced EMB ensemble, the late 20th and early 21st centuries are characterized by the dominance of reinforcing economic feedback processes that seem to operate independently of environmental constraints. In this phase, the system behaves as a self-referential economic growth engine, primarily driven by the reinforcing cycle of capitalism which we refer to as the *core economic engine* (Figure 2): investment stimulates employment, production and wage increases, which in turn fuels consumption, creating demand pressures fueling further investment. Accumulated investment into fossil energy and the low marginal cost of fossil fuels create a path dependency, suppressing the early adoption of renewables (which remain below 13% share in all runs until 2020). The reinforcing nature of this process (*learning by doing fossils*), where learning-induced cost reductions in fossil energy stimulate the investment and capital accumulation required to extract more energy, entrenches the path dependency. This period effectively locks in the emissions trajectories that define the middle and end of the simulation period, creating a "sunk cost" dynamic that resists transition. While the balancing *inflation governor* process between wages and inflation successfully moderates inflationary pressures by ensuring that supply factors moderate demand-induced growth pressures (keeping inflation generally between 1–6%), environmental impacts ("externalities") accumulate largely unchecked, since their consequences in terms of societal and economic costs are delayed and subject to significant uncertainty related to both magnitude and distribution (*future investment spiral, future climate driven investment governor and future climate driven consumption governor*). The balancing processes in this time period are macroeconomic governors, not Earth system limits; they regulate the rate of economic growth but do not constrain economic activity, contributing to the overshoot of biophysical limits. Meanwhile, even though Surface Temperature Anomaly (STA) rises from $\sim 0.25^{\circ}\text{C}$ to $\sim 1.1^{\circ}\text{C}$ (see Figure 1a), its impact in this time period is limited.

The mid 21st century

The mid 21st century marks a phase transition where the system's behavior is no longer dictated solely by the economic growth engine but increasingly by Earth system constraints as depicted in Figure 3. This period is defined by a tension between the inertia of the core economic engine, and its associated demands on natural systems, and the increasing strength of balancing feedbacks that challenge its trajectory. It is the strength of these biophysically-driven balancing climate impact processes and the sensitivity of the economic system to changes in the Earth system that determine the overall behavior of an ensemble member. Outcomes are split between runs which maintain, albeit diminished, exponential economic growth, and those which grow linearly or even shrink (see Figure 1b). Examples of biophysical limits include, for instance, land-use constraints: as the agricultural sector faces the need to feed a growing and increasingly wealthy population with more animal products, while simultaneously decarbonizing via biofuels, it encounters constraints to agricultural land expansion. This manifests as

competition for arable land and agricultural intensification, driving both deforestation and soil degradation, due to agricultural intensification. The feedback processes here become complex: biofuel production exacerbates food supply pressures (creating inflationary pressures). This is just one example of the challenges associated with substituting fossil capital, and FRIDA illustrates how this results in an energy transition gap where reductions in fossil fuels are not immediately offset by renewables due to weakened *learning-by-doing* effects (i.e., slower renewables cost reductions and efficiency gains). This gap induces periods of increased economic volatility and inflation (see Figure 1e). Most importantly, we observe the onset of "drag-inducing" climate-driven governor feedback processes where the increases in STA and accompanying climate impacts begin to significantly reduce investment. The natural environment shifts from a passive sink to an active constraint as the overlooked environmental "externalities" of the 20th century start to exert their impacts – though the combined natural and human system retains enough robustness to absorb these impacts, initially.

A critical emergent property across all simulations is the nonlinear behavior of food demand and renewable energy adoption. Initially, rising incomes drive an increase in meat and other animal-derived products consumption; however, as the surface temperature anomaly breaches 1.5°C (circa 2030) and approaches 2.5°C (circa 2060), the climate risk perception processes dominate (*climate driven behavior change*). In most runs, animal product demand peaks between 2040 and 2060 at 600-700 kcal/person/day versus the present-day amount of ~525 kcal/person/day and then falls (see Figure 1g). This represents a societal phase shift where the perceived risk of climate change contributes to overriding income-elastic demand preferences.

During this window, the energy transition accelerates, driven by the widening cost gap between renewables and depleting fossil resources. Renewable energy share climbs from ~12% in 2020 to 40–50% by 2070 (see Figure 1i). Yet this transition is not smooth. In several runs, stranded fossil energy assets create financial instability (*fossil devaluation*). As the physical reality of climate change and shifting energy investments forces a move away from fossil fuels, the stock of fossil capital undergoes devaluation. This harms financial agents' portfolios, spikes risk premiums, and reduces the investment growth into renewable energy and other adaptation and mitigation measures (*interest caused failures*). The financial sector, previously an engine of growth, diverts surplus away from innovation to protect existing wealth, sacrificing growth and slowing the sustainability transition by limiting investments in renewable energy.

The late 21st century to the mid 22nd century

By the late 21st century and into the mid 22nd century, the system settles into a new regime shown in Figure 4. Economic growth is significantly reduced, with more pronounced boom and bust cycles caused by climate impacts on the socioeconomic system (see Figure 1b). The dominant feedback processes shift from reinforcing growth to climate damage-driven dynamics, including financial disruptions from failing loans, sea level rise damages, increases in mortality and productivity losses (*investment spiral*,

climate driven credit governor, climate driven consumption governor, labor productivity spiral, climate driven mortality in Figure 4). As STA begins to stabilize between 2°C and 6°C (Figure 1a), accumulated climate impacts act as a significant drag on the economy's growth potential.

The aforementioned climate impacts constrain economic output growth, and, consequently, the capacity to renew damaged infrastructure or invest in mitigation, leading to further warming (*investment spiral, labor productivity spiral*). This creates a vicious cycle where the economy progressively loses its capacity to sustain growth. Only when significant reductions in demand for emission-intensive goods (energy and food) are achieved do the spirals begin to slow. By this point, the *core economic engine* process, previously the main engine for growth, has largely been supplanted by the effects of climate. The result is tighter lending conditions, reduced investments, and persistent unemployment (approaching a steady-state 10% in bleak runs).

Population dynamics also shift during this period, moving from reinforcing growth to balancing decline. Global population peaks in the 10–12 billion range around 2080–2090 before entering a sustained decline (see Figure 1c). In cooler runs, population dynamics follow a standard demographic transition driven by rising wealth. In all cases, the demographic transition comes too late to balance the powerful climate change inertia accumulated through the 20th century. In the hottest simulations, this decline is accelerated by the *climate driven mortality*, which increases deaths among people aged 0-75 by up to 11%, and among those older than 75 by up to 18% in 2150.

4. Discussion

This transition is not caused by a single climate impact channel. Instead, it arises from interactions among multiple sectors, including energy systems, land use, demographic change, finance, and climate damages. The results therefore suggest that long-term development pathways are determined not only by the magnitude of climate impacts but also by the structure and timing of feedback interactions that connect human and Earth systems.

FRIDA simulates the co-evolution of the human and Earth system without exogenous input¹, providing a process-based account of a non-policy-impacted, global system in which the ordering of feedbacks (rather than any single sector) governs long-run outcomes. In early decades, reinforcing macroeconomic loops (*core economic engine*) dominate; later, as accumulated impacts from climate change materialize, largely balancing biophysical loops (i.e., climate damages to productivity, finance, and mortality, etc.) progressively constrain the human system. The reduced EMB ensemble exhibits a consistent loop dominance shift: late 20th to early 21st century dynamics are growth-seeking and financially moderated, while late 21st–22nd century dynamics are impact-limited and volatility-prone. In the initial phase, fossil-fuel path-dependence is reinforced through learning-by-doing and low marginal costs, suppressing early renewable adoption. As warming accumulates from ~0.25 °C in 1980 to ~1.1 °C in the present-day, the climate system becomes the latent driver of future constraints. In the mid-21st century, land competition between food and biofuels, soil carbon losses, and heat-induced labor productivity declines begin to

erode the autonomy of the growth engine. By the late 21st century, loop dominance transitions to climate-damage-driven governors (e.g., *investment spiral*; *climate-driven credit and consumption governors*; *labor productivity spiral*; *climate driven mortality*), introducing stabilizing pressures that suppress investment, tighten credit, slow capital turnover, and lower trend growth. These patterns resonate with calls for fully coupled world-Earth models that can trace cross-system feedbacks beyond single-channel damage functions (Moore et al., 2022; Otto et al., 2020).

Empirical, top-down estimates suggest climate impacts can be large yet are sensitive to method and context (Burke et al., 2015; Kotz et al., 2022); see also debates on methodological uncertainty in damages (Morris et al., 2025; Stern et al., 2022). FRIDA's process-based orientation complements these statistical approaches by attributing changes in system behavior to traceable feedback structures rather than reduced-form coefficients. Through loop dominance analysis, FRIDA makes explicit which feedback processes govern behavior at different moments in the coupled system's evolution, providing traceability and interpretability not accessible in empirical estimates or reduced-form IAM damage functions.

Across ensemble runs, financial dynamics do not ignore climate risk; they internalize it late and nonlinearly. As biophysical impacts intensify in the mid-21st century, banks remain exposed to fossil capital due to historical profitability and learning-curve advantages. When devaluation arrives, it propagates through observed defaults to tighter lending standards and higher risk premiums for all loans, which then suppress not only fossil investment but also investment into renewables, adaptation, exploratory investments that create innovation, and general economic activities. Reductions in exploratory investment is a key mechanism by which climate stress impacts economic development pathways, because it is these investments which drive innovation and increases in productivity that lead to continued economic growth.

Interest-caused failures amplify downturns: higher loan failure rates raise refinancing costs, inducing further failures. This is not “market failure” in a narrow sense, but a mismatch of financial time-constants: a system optimized for risk control is ill-suited to manage slow-accumulating, system-wide, uncertainty. Increased ambiguity can rapidly deteriorate the financial markets ability to support economic growth (Boyarchenko, 2012). This aligns with broader concerns that damage-function and financial-stability uncertainties can render point estimates misleading and that process-based diagnostics are needed to interpret macro-financial responses under climate change (Morris et al., 2025; Stern et al., 2022).

All runs in the reduced EMB ensemble ultimately feature mitigation technology deployment (e.g., renewables) and behavioral adaptation (e.g., diet shift, demand moderation). Yet both changes occur too late to prevent the global system from entering a climate-impact-dominated regime. Technological scaling is slowed by the sunk costs of historical investments into fossil capital, financing headwinds, the resource intensity of the build-out, and weakened learning-by-doing under macro stress. Behavior-change feedback processes strengthen only once climate risk perception overwhelms income-elastic preferences, often after the system has crossed 1.5–2.5 °C. In multiple runs, stranded assets and the

defaults they cause increase risk premiums that result in dampened renewable investment, delaying the very mitigation needed to relieve climate damage loops. These patterns align with System Dynamics research showing that late, damage-driven responses emerge when feedback-rich systems lack early anticipatory interventions, underscoring the need for feedback-aware, process-based approaches to understanding social–ecological transitions ([Collste et al., 2025](#); [Elsawah et al., 2020](#); [Liu et al., 2007](#); [Piontek et al., 2021](#)).

Endogenous delays, long-lived physical capital, institutional and cultural inertia, and signal-to-noise challenges produce hysteresis: even after incentives flip, reallocation takes years to decades. FRIDA's reduced EMB ensemble trajectories thus portray a re-coupling of the macroeconomy to Earth-system constraints that is not smooth but punctuated by volatility in economic output, inflation, and employment. In warmer runs, climate-driven mortality and productivity losses accelerate the descent toward low-growth equilibria; in cooler runs, demographic transitions occur, but too late to offset the inertia of 20th-century emissions and historical investments into fossil fuel assets. These findings are consistent with critiques that single-channel IAM damage representations may understate system-wide effects by omitting feedback complexity, consequently resulting in optimistic baselines ([Howard and Sterner, 2017](#); [Moore et al., 2022](#); [Robinson et al., 2018](#)).

The results imply that policy is not optional: it is the mechanism by which human society decides whether coupling to biophysical limits occurs as Peter Victor ([2019](#)) calls it, by design or by disaster. Three key policy domains for earlier, more stable, and more equitable pathways can be identified:

- Financial system architectural changes: capital regulation, climate-aligned insurance, and countercyclical green credit facilities to prevent climate-induced tightening from choking mitigation and adaptation (addressing the credit-governor and interest-failure loops).
- Energy system policy: early and durable incentives that break fossil learning-by-doing and avoid disorderly fossil devaluation; policies that preserve renewable investment through downturns (contracts-for-difference, green public banks).
- Demand-side and behavioral policy: accelerating dietary shifts and changes in energy use before climate damages force reductions, aligning preferences and norms with the planetary limits, and thereby reducing the strength of biophysical feedback loops.

There are several limitations inherent to a global-scale model seeking to represent the development of the human-Earth system over a century into the future. While FRIDAv2.1 internalizes multiple impact channels (e.g. productivity, mortality, infrastructure, finance) and endogenizes demographics and investment, energy-service demand remains tied closely to GDP in the current version. In turn, reductions in energy demand are largely mediated through macroeconomic contraction. Better representations of behavioral feedbacks in energy use could reduce the gain of late-century reinforcing processes such as investment spiral and labor productivity spiral, without requiring recessions. The set of modeled impact channels is large but incomplete, currently excluding highly localised impacts as well as representations of Earth system tipping points. The focus on global aggregated feedback complexity is appropriate for

identifying the dominant system-wide feedback structures, but it masks regional heterogeneity in all domains, including trade, geopolitics, and human and biophysical responses to both global and local environmental changes. Regionalizing FRIDA in the future would enable distributional assessment, finer detail in climate impact modeling, and targeted policy design. Yet such regionalization risks weakening FRIDA's core strength: identifying the global-scale feedbacks that are more easily observed and measured in an aggregated global representation.

The decisive factor is not a lack of solutions but the lag in their deployment relative to accumulating damages. The system's endogenous delays, financial, infrastructural, and social, allow reinforcing growth dynamics to stockpile risk that later manifests as dominant biophysical governors. The strategic choice is therefore not whether biophysical constraints will bind, but whether agency is exercised early enough to shape how they do – a distinction that echoes the classic “by design or by disaster” framing (Victor, 2019) referred to above. In FRIDA, absent anticipatory policy, the re-coupling of the global economy to the Earth system occurs under duress, with lower growth, more volatility, and diminished adaptive capacity. With policy that targets these identified feedback processes, the same system may exhibit pathways that are more stable, more equitable, and potentially with limited pressures against planetary limits.

5. Conclusion

This study used feedback loop dominance analysis within the fully coupled FRIDAv2.1 integrated assessment model to investigate how interactions among climate, economy, population, energy, and land-use systems shape long-term global development. By analysing representative simulations from a large endogenous scenario ensemble, we identified the feedback processes responsible for behaviour across different phases of human-Earth system evolution.

Three main findings emerge. First, system behaviour during the late twentieth and early twenty-first centuries is primarily governed by reinforcing economic growth feedbacks. During this period, learning effects, investment dynamics, and expanding consumption sustain growth while climate impacts remain relatively weak and delayed. Second, the mid twenty-first century represents a transition period in which climate impacts increasingly interact with economic and financial processes. Climate-driven effects on productivity, land use, investment, and financial stability progressively weaken the dominance of growth-oriented feedbacks and increase system volatility. Third, in many futures, the late twenty-first century is characterised by the emergence of climate-impact-driven balancing feedbacks. These processes constrain investment, reduce adaptive capacity, alter demographic trajectories, and limit further economic expansion. The resulting behaviour reflects a progressive re-coupling of socio-economic development to biophysical constraints.

The principal contribution of this work is methodological as well as substantive. By combining fully coupled integrated assessment modelling with quantitative feedback analysis, we move beyond

describing future outcomes to explaining the processes that generate them. This provides a transparent framework for identifying when and why dominant system drivers change over time.

The results suggest that technological progress and behavioural adaptation alone may be insufficient if they emerge only after climate impacts have become major determinants of system behaviour. Future work should extend this analysis through regional disaggregation, improved representation of behavioural and institutional responses, and the inclusion of additional Earth-system feedbacks. More broadly, the findings highlight the importance of understanding climate change as a dynamic feedback problem within a coupled human-Earth system rather than as a collection of isolated sectoral impacts.

Declarations

Author Contributions:

Conceptualization: WS, JKR, BK. Investigation: WS, JKR, CW, BK, DC, BB, BC, ANL, AK. Software: WS, BB. Validation: WS, JKR, CW, BK, BC, DC, AK. Visualization: WS, JKR, BB, DC. Writing – original draft: WS, JKR, CW, DC, BK, BC, ANL, AK, BB. Writing – review & editing: WS, JKR, CW, DC, BK, BC, ANL, AK, BB.

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Footnotes

1. The only exogenous drivers in FRIDA are the solar radiation cycle, Montreal Protocol GHGs, and forcing from volcanic eruptions.

Figures

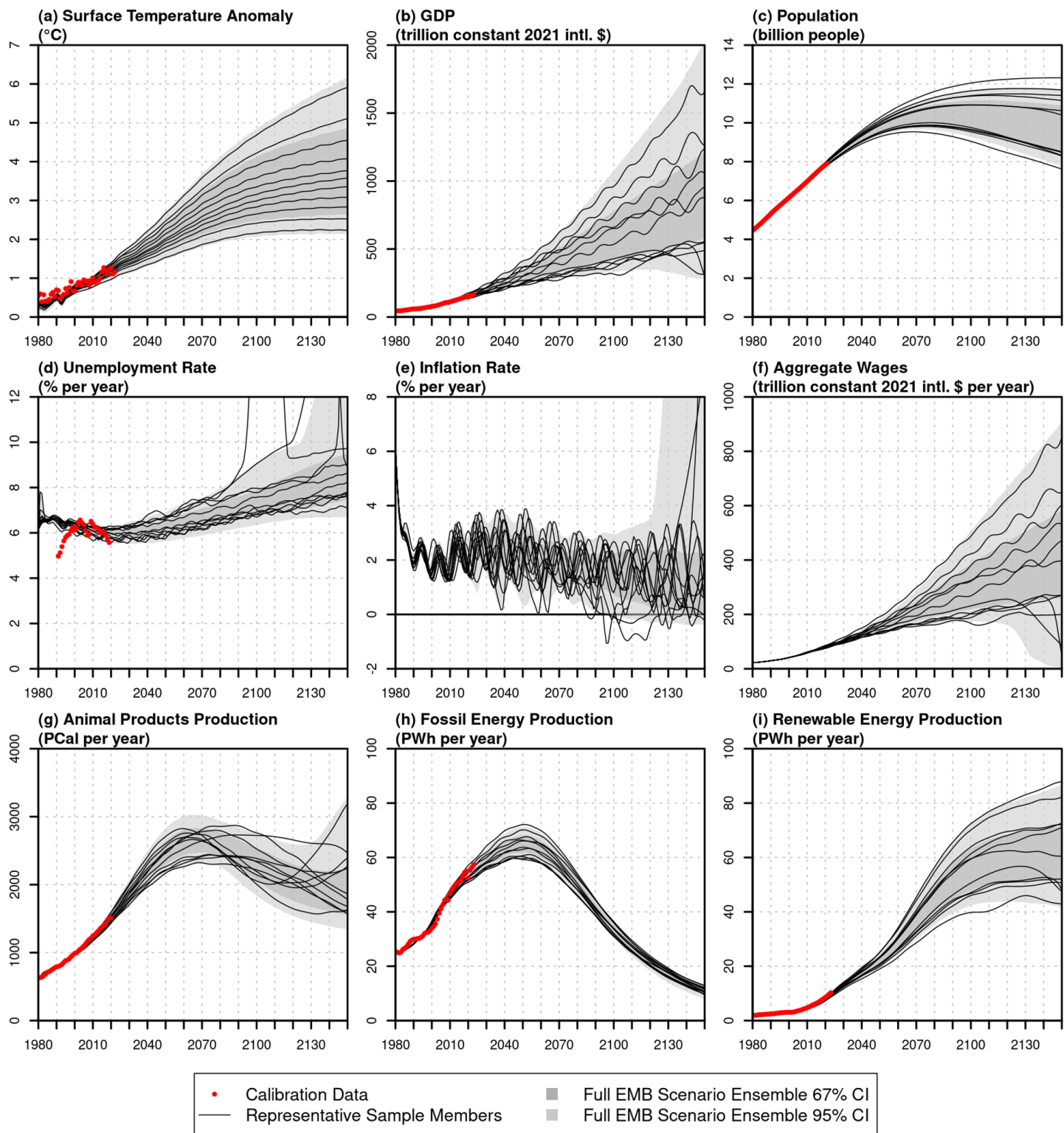


Figure 1

Results from the 11 runs in the reduced uncertainty ensemble plotted on top of the full 100,000-member EMB scenario ensemble from 1980-2150 including historical calibration data where present. Outputs are (a) Surface Temperature Anomaly in degrees Celsius, (b) Real Gross Domestic Product (GDP) in trillions of 2021 international constant dollars, (c) Population in billions of people, (d) Unemployment Rate in percent per year, (e) Inflation Rate in percent per year, (f) Aggregate wages in trillion constant in trillions

of 2021 international constant dollars, (g) Animal Products Production in petacalories per year, (h) Fossil Energy Production (secondary energy) in petawatt hours per year and (i) Renewable Energy Production in petawatt hours per year. The FRIDA EMB scenario ensemble is in the shaded grey, the dark lines are the representative samples, darker area is the 67 % confidence bounds, lighter area is the 95 % confidence bounds. Calibration (Historical Data) for each plot is in red.

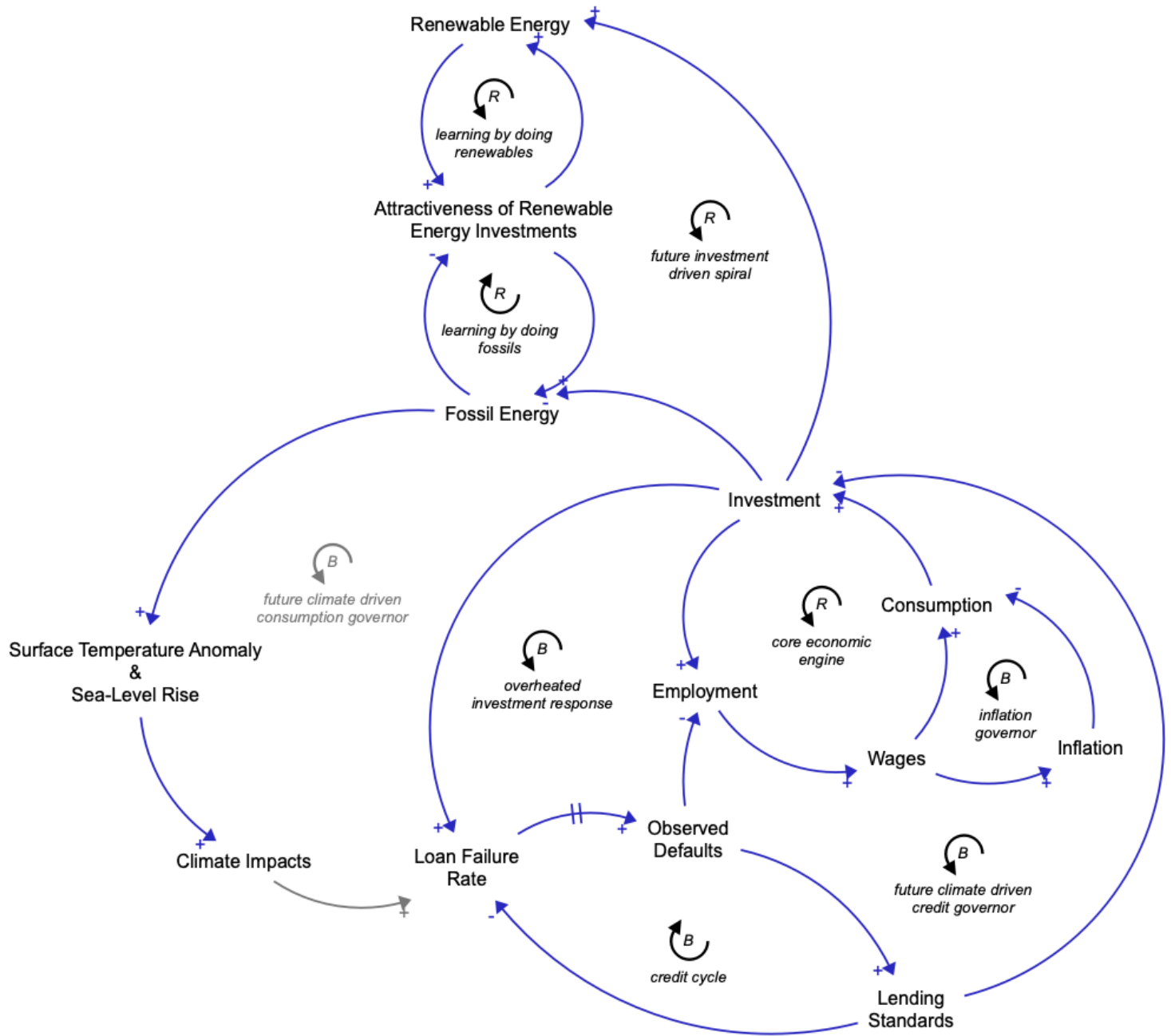


Figure 2

Feedback processes driving the behavior of the reduced EMB ensemble in the late 20th and early 21st century. This feedback structure is the core of the human economic system which determines outcomes throughout the entire simulation period. Wages, consumption and investments are in real terms. The grey links and loops are those that will become relevant in the future.

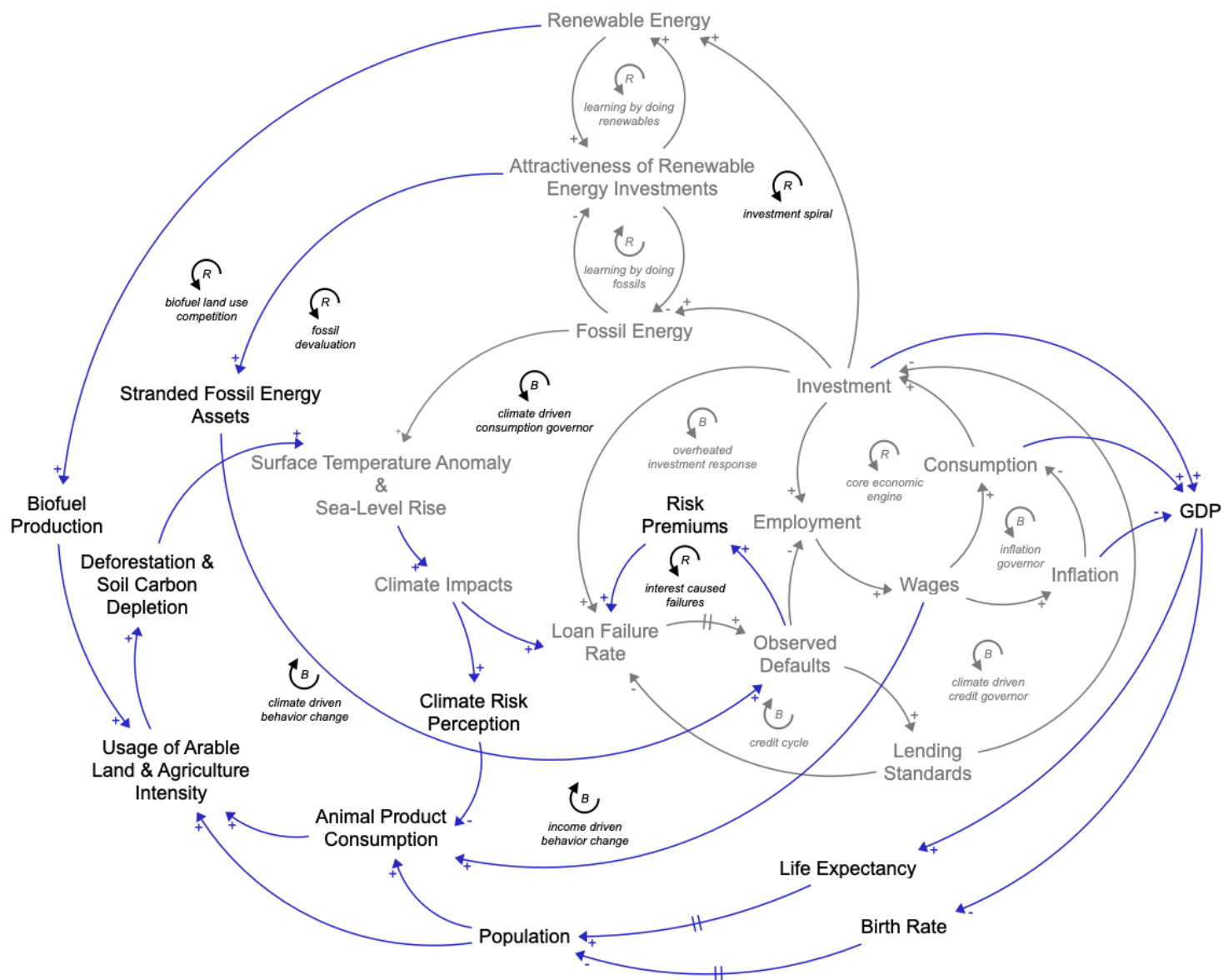


Figure 3

Feedback processes driving the behavior of the reduced EMB ensemble in the mid 21st century, including strong balancing climate impacts which slow the momentum of the economic system (in grey) shown in Figure 2.

