



An overview of FRIDA v3.1: An update to a feedback-based, fully coupled, global integrated assessment model of climate and humans

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Abstract. The Feedback-based knowledge Repository for Integrated Assessments (FRIDA) v3.1 is a fully coupled climate-human systems model designed to explore the global long-term co-evolution of environmental, technological, economic, financial, and social processes under deep uncertainty. While many integrated assessment models represent climate damages primarily through aggregate economic impacts, important feedbacks among human behaviour, energy systems, land use, climate impacts, technological change, and financial stability remain weakly represented or exogenous. FRIDA v3.1 addresses this limitation through a system dynamics framework that embeds these processes within a unified feedback-rich structure, enabling emergent dynamics to arise from interactions across sectors rather than from externally prescribed assumptions. Building on earlier model versions, FRIDA v3.1 introduces representations of climate-driven wildfire dynamics, endogenous fertilizer use, sectorally disaggregated and behaviourally-informed energy demand, climate impacts on wind energy productivity, endogenous life expectancy, carbon capture and storage technologies, and macro-financial policy mechanisms designed to reduce climate-related financial risks. The model integrates these additions with existing representations of the climate system, carbon cycle, hydrology, population, economy, agriculture, land use, and energy supply. Calibration and evaluation against a large historical dataset and extensive uncertainty ensembles show that the updated model reproduces history while generating novel feedbacks that influence future development pathways. FRIDA v3.1 advances the capacity of integrated assessment modelling to investigate how behavioural, biophysical, technological, and financial processes jointly



35 shape climate outcomes, providing a transparent and computationally efficient platform for uncertainty analysis, scenario exploration, and policy assessment in a rapidly changing world.

1 Introduction

FRIDA, *Feedback based knowledge Repository for IntegrateD Assessments*, is a fully coupled global integrated assessment model (IAM) developed to study the long-term co-evolution of the coupled human and natural system under socioeconomic and climatic uncertainty (Schoenberg et al., 2025). The model represents the carbon cycle, the physical climate system, and its
40 impacts on the human system, including population, economic development, energy and food demand and supply, land use, and agriculture (see Grimeland et al., 2026; Rajah et al., 2025; Ramme et al., 2025; Schoenberg et al., 2025; Wells et al., 2026b, a). FRIDA's endogenous model behaviour (i.e., change over time) arises from feedback interactions among these components, consistent with the System Dynamics tradition (Forrester, 1961; Sterman, 2000) that the model is based on.
45 FRIDA was designed for large ensemble analysis, remaining computationally efficient enough to support system-wide exploration of uncertainty while retaining sufficient detail to reproduce key historical patterns across multiple subsystems (Schoenberg et al., 2025). The first published version, FRIDA v2.1 (Schoenberg et al., 2025), can be used to support a range of analyses of the coupled human–climate dynamics, including uncertainty-aware assessments based on large ensemble simulations and scenario comparison (e.g., Rajah et al., 2026; Schoenberg et al., 2026b). Its primary function is therefore to
50 support systems understanding and rapid system-wide experimentation, enabling exploration of the behavioural implications of alternative assumptions and interventions (Mauritzen, 2026).

Realizing this function requires sufficient representation of the processes through which human decisions, economic conditions, climate impacts, and natural-system changes interact. Scholars have widely discussed the limitations in how many mainstream IAMs represent demand, behaviour, and climate impacts (e.g., Asefi-Najafabady et al., 2021; Beckage et al., 2022;
55 Gambhir et al., 2019; Keen, 2021; Mathias et al., 2020; Otto et al., 2020). Highly aggregated or exogenously specified formulations can obscure processes that arise endogenously from interactions across sectors, particularly where sectoral structure, individual decision-making, and nonlinear climate responses jointly shape system behaviour. Such limitations constrain the questions those IAMs can credibly address, especially when policy outcomes depend on feedbacks that fall outside, or remain weakly represented within, their existing model boundaries. FRIDA v2.1 faced several corresponding
60 limitations in the representation of energy demand; fertilizer use; carbon capture and storage (CCS) and carbon dioxide removal (CDR) deployment; wildfire dynamics; and climate-related financial risk. Although these domains concern distinct system components of the coupled system, their further development addresses a common representational problem: potentially consequential processes that mediate interactions between human and natural systems were either aggregated, prescribed exogenously, or omitted. FRIDA v3.1, documented here, introduces five principal extensions that strengthen feedback
65 representations in energy demand, agriculture, mitigation technology, wildfire disturbances, and climate-related financial risk.



These extensions are accompanied by selected revisions to existing model components and the introduction of additional indicators and climate-impact relationships.

The first extension revises the representation of energy demand through sectoral disaggregation and an endogenous behavioural formulation of transport energy use. Although energy use is strongly linked to population and economic activity/output, formulations based primarily on these aggregate drivers and climate, provide limited insight into the processes determining energy demand across sectors (Krysiak and Weigt, 2015). Specifically, such highly aggregated representations can overlook important dynamics, including changes in the sectoral composition of demand, behavioural responses to imbalances in the energy supply and demand, and the influence of climate on those responses. FRIDA v2.1 employed such an aggregate formulation, limiting its capacity to examine how these processes interact with wider macroeconomic and climatic dynamics. Consistent with the importance of sectoral differentiation highlighted by Filippov et al. (2021), FRIDA v3.1 differentiates energy demand among buildings, transports, and industry and other uses. Within this disaggregated structure, transport energy is represented as an endogenous outcome of behavioural, economic, and technological conditions.

The second extension introduces an endogenous representation of fertilizer use in agriculture. Fertilizer application is commonly represented as a technical input derived from crop production requirements (Bodirsky et al., 2012; Mogollón et al., 2018) or specified exogenously (Von Bloh et al., 2018). In practice, however, fertilizer use reflects decisions made by farmers under changing economic and environmental constraints (Moritz et al., 2026; Sheriff, 2005; Vos et al., 2025). FRIDA v2.1 did not represent these decision processes endogenously, limiting its capacity to examine how fertilizer use responds to, and subsequently affects agricultural production, economic conditions, and climate outcomes. FRIDA v3.1 links farmer decision-making to conditions within the coupled agricultural, economic, and climate system, allowing fertilizer use to emerge as an endogenous model outcome.

The third extension more closely connects the deployment of CCS and CDR to conditions within the energy, economic, and climate systems. CCS and CDR technologies are often included in mitigation scenario analyses, but their deployment is typically prescribed through exogenous scenario assumptions (IEAGHG, 2021; Muratori et al., 2020; Weyant, 2017). Although this approach permits comparison among alternative deployment pathways, it provides limited insights into how deployment may emerge from interactions among economic development, energy systems, and climate outcomes. In FRIDA v2.1, CCS and CDR were largely absent. FRIDA v3.1 introduces a more endogenous representation, enabling exploration of how deployment responds to changing conditions within the coupled system and, in turn, influences subsequent economic and climate outcomes.

The fourth extension incorporates wildfires as a disturbance process linking the carbon cycle, ecosystem structure, land surface properties, and human societies. Despite these cascading cross-system consequences, wildfire dynamics remain underexplored in current IAMs and were absent from FRIDA v2.1, presenting a structural gap in the understanding of how disturbance



processes shape long-term climate-society trajectories. When fire occurs, it simultaneously affects multiple Earth system components: large quantities of CO₂, CH₄, N₂O and aerosols are released into the atmosphere during combustion, modifying the radiative balance of the Earth, while black carbon in smoke influences precipitation formation and reduces snow and ice albedo in the cryosphere (Bowman et al., 2020). Burned area is a well-established and widely used metric to quantify wildfire activity, capturing the spatial extent of fire disturbance and serving as the basis for estimating a broad range of downstream impacts (Bowman et al., 2020; Giglio et al., 2018). FRIDA v3.1 introduces a climate-driven representation of burned area and connects its consequences to other components of the model, allowing the effects of wildfire disturbance to propagate through the coupled system under climate change.

The fifth extension represents the implications of climate-related damages for financial stability. Increased climate-related risks to economic activity can lead to higher loan failure rates (Schoenberg and Callegari, 2025), with significant consequences for investments and long-term economic growth. However, most IAMs do not explicitly represent the financial risk implications of climate change. While FRIDA v2.1 represented the financial mechanisms through which climate damages could propagate through the global macroeconomy, it did not capture how insurance and government investment respond to, and potentially modify these effects. FRIDA v3.1 introduces these additional feedbacks, enabling examination how insurance mechanisms and government investment may redistribute or mitigate the economic impacts of climate-related financial stress.

In addition to these five principal extensions, FRIDA v3.1 includes several supporting developments within existing model components. The climate and carbon cycle components incorporate updated calibration and selected formulation changes developed in conjunction with FRIDA-Clim (Wells et al., 2026a). The energy module now represents climate-related changes in wind-energy full-load hours, introducing an additional connection between climatic conditions and energy supply. A global life-expectancy indicator was also added to the Demographics module, calculated from age-specific mortality rates already represented in FRIDA v2.1. These development revise existing formulations, but do not fundamentally change or extend the existing feedback structure of the model.

In this paper, we document the conceptual basis, implementation, and evaluation of the principal extensions and supporting developments comprising FRIDA v3.1. We first describe their integration within the existing FRIDA structure, organized by the relevant top-level module. We then evaluate the updated model by comparing its ability to reproduce historical behaviour, comparing its endogenous model behaviour with that of FRIDA v2.1, and tracing the trajectories generated by selected new structures. Finally, we use stylized experiments to demonstrate the operation of the new CCS and macro-financial policy structures. These analyses provide a transparent account of the developments distinguishing FRIDA v3.1 from the previously documented v2.1 and establish the basis for its future use by the IAM community.



2 Model developments from FRIDA v2.1 to FRIDA v3.1

FRIDA v3.1 retains the overall modular architecture of FRIDA v2.1 while revising or extending several processes within the seven top-level modules: Climate, Land Use and Agriculture, Energy, Behavioural Change, Resources, Demographics, and Economy. The following subsections describe these developments according to the top-level module in which they are implemented, while tracing their connections to other parts of the model. For example, the decision processes governing fertilizer use and transport energy demand are implemented within the Behavioural Change module, but their consequences propagate through the Land Use and Agriculture and Energy modules, respectively. The developments differ in scope: some introduce new endogenous feedback structures, whereas others revise existing formulations, update calibration procedures, or derive new indicators from existing model behaviour. The full model code for FRIDA v3.1 can be obtained from Schoenberg et al. (2026a).

2.1 Climate module

The climate system components of FRIDA v2.1 reproduced key historical observations and generated future projections consistent with those of reduced- and full-complexity complexity models. Their overall architecture was therefore retained in FRIDA v3.1, with selected changes arising from the continued development and calibration of the standalone FRIDA-Clim model (Wells et al., 2026a).

FRIDA-Clim was developed by separating the Climate module from the rest of FRIDA, allowing the climate and carbon cycle components of the model to be evaluated independently under external forcing inputs, ranging from idealised experiments to future scenarios (Wells et al., 2026). FRIDA-Clim v1.0.1 corresponds to the climate and carbon cycle representation used in FRIDA v2.1. Subsequent developments in the production of FRIDA-Clim have been incorporated into FRIDA v3.1 through a revised calibration procedure. The land carbon cycle is now calibrated together with the ocean carbon cycle and the other components of the Climate module before their integration into the coupled model. Thereby, sets of internally consistent climate cases that reproduce the observed carbon cycle and temperature trends are loaded into FRIDA. The variables that are now dependent on the climate case encompass those from the soil carbon formulations, the net primary production sensitivities to climate variables for grassland and forests, as well as the initial stocks of aboveground biomass and forest areas. Alongside this calibration update, one structural change was made in the functional form of the change in grass and forest net primary production (NPP) to atmospheric CO₂. The prior linear relationship was revised to a logarithmic one, allowing for a saturation of this effect as atmospheric concentrations increase, rather than continuing to increase proportionally throughout the simulation.

Additionally, through the process of contributing to the Reduced Complexity Model Intercomparison Project (RCMIP) phase 3 (Romero-Prieto et al., 2026), the model was recalibrated using the RCMIP-supplied inputs and framing, including replacing the range of 1750 CO₂ concentrations with the single RCMIP-supplied value. Even though the necessary adaptations in FRIDA



are only of a technical nature and do not introduce new feedback, the inclusion of the new structure required a recalibration of the FRIDA Land Use and Agriculture module, including its new wildfire impact (see Sect. 2.2.1 below). These changes also comprise the new version FRIDA-Clim v1.2.0 (Wells and Ramme, 2026).

60 2.2 Land Use and Agriculture

FRIDA v3.1 extends the Land Use and Agriculture module by introducing an explicit representation of climate-driven fire disturbance. The new structure links global mean surface temperature anomaly (STA) to burned area and its consequences for land productivity and carbon flows. Fertilizer use also affects agricultural productivity and land requirement within this module, but the decision processes governing fertilizer demand are implemented in the Behavioural Change module and are described in Sect. 2.4.2.

2.2.1 Climate-driven wildfire disturbance

FRIDA v2.1 represented climate impacts on terrestrial productivity and land allocation but did not include wildfire disturbance. FRIDA v3.1 introduces this pathway through overburned area, a key impact and standard metric to quantify wildfire activity, defined as the additional global area burned due to anthropogenic climate change relative to a counterfactual without climate change. The structure is not intended to reproduce total wildfire activity or the processes governing individual fire events. Instead, it represents the additional disturbance attributable to climate change and its consequences for the land and carbon system.

The relationship between climate change and wildfire disturbance is parametrized using the global estimates from Burton et al. (2024), who quantify the contribution of anthropogenic climate change to increases in global burned area. Specifically, we use their global percent of “overburned area” (i.e. additional area burned due to climate change) and express it as a function of STA to represent the global impacts of climate-driven wildfires in FRIDA (Fig. 1). A quadratic fit between STA and total overburned area due to climate change is applied. The resulting total overburned area is then allocated to each FRIDA land-use type (cropland, grassland, forest - young and mature) using burned-area fractions derived from the observation-based MODIS burned area product (MCD64A1 in Giglio et al., 2018). The percentage of overburned area is defined relative to an estimated area that would have burned in 1980 in the absence of anthropogenic climate change.

The consequential impacts of the overburned area are treated differently for each land use type represented in FRIDA: grassland, cropland, young forest, and mature forest. For grasslands, which account for ~90% of the total overburned area, burning reduces grassland net primary production (NPP) and renders the land unusable for one year. Similarly, burned cropland reduces the usable cropland stock and associated NPP, with a one-year “out-of-service” period. For forests, burning affects young and mature forests equally, according to their relative area. Burned mature forest area is then transformed into young forest, analogous to logging. For both types of forest, all aboveground biomass is lost either as emissions of CO₂ to the atmosphere or as a transfer of carbon to the soil. The distribution between the two is an uncertainty parameter, with the majority



of carbon going to the soil. This additional flux of carbon to the soil, in combination with the reduced productivity of young forests in FRIDA, leads to a relative increase of young forest soil carbon per area, and hence a delayed flow of CO₂ from the soil to the atmosphere due to burning, as some of the additional biomass is respired. However, due to the choice of parameterizations the model likely provides a conservative estimate of this delay, as it does not represent pyrogenic carbon which can persist for centuries, beyond the turnover time of even FRIDA’s slowest soil carbon pool. Nevertheless, the resulting structure introduces a pathway through which climate-driven wildfire disturbance is connected to land productivity, forest age structure, terrestrial carbon storage, and atmospheric carbon emissions.

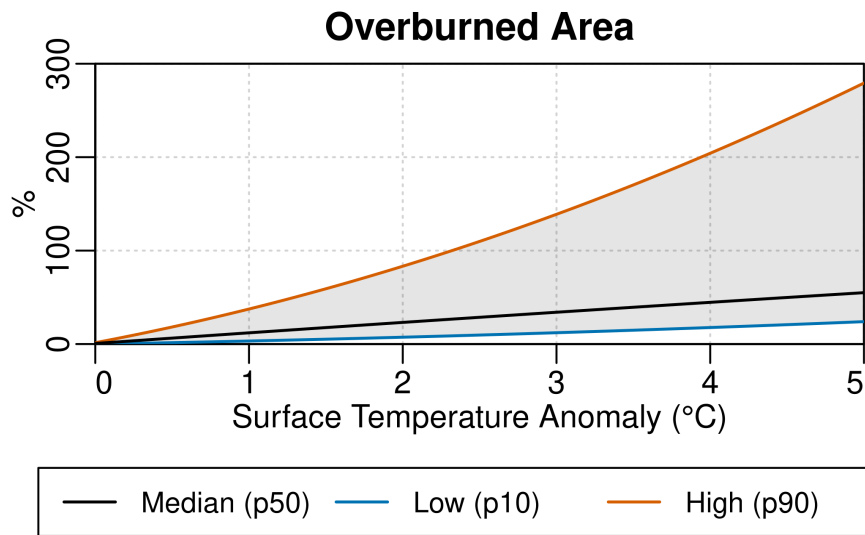


Figure 1. Global “overburned area” (additional burned area attributable to anthropogenic climate change, in percent, based on Burton et al. (2024)) as a quadratic function of global mean surface temperature anomaly for the median, high, and low cases.

2.3 Energy module

FRIDA v3.1 modifies the Energy module in two respects: (1) aggregate final energy demand is disaggregated across major end-use sectors, allowing sector-specific demand trajectories and policy intervention to be examined; and (2) wind power availability is made responsive to changing climatic conditions, introducing a pathway from endogenous climate change to renewable electricity generation. These modifications increase the sectoral specificity of energy demand and strengthen the representation of climate–energy feedbacks.

2.3.1 Energy demand disaggregation



FRIDA v2.1 represented energy demand at the global aggregate level. In FRIDA v3.1, this demand was disaggregated across three major sectors following the International Energy Agency (IEA) sectoral classification, consisting of (i) buildings (residential and commercial/public services), (ii) transport, and (iii) industry and other. Demand in each sector is implemented using a power function regression that evolves as a function of GDP. Sector-specific parameters determine the responsiveness of demand to economic growth, capturing the slow increase in energy consumption in the first decades, as well as the expected long-term increases in demand until and beyond the end of the century. The existing representation of energy use changes from heating and cooling demand is further incorporated into the buildings sector, maintaining the link between STA and energy use while locating the final end-use within the sector in which they predominantly occur.

This resulting structure represents an intermediate step towards a more refined sectoral disaggregation, enabling the study of energy and demand-related policies within FRIDA in a simplified yet meaningful way. While the representation of energy demand as a GDP-dependent regression does not capture the full complexity of sectoral drivers, it allows for an initial exploration of how macroeconomic trends and broad policy shifts could affect this disaggregated energy demand. For instance, the framework can be used to test stylized scenarios of efficiency improvements, or structural economic changes, by adjusting parameters that influence the relationship between GDP and energy demand growth per sector. Within the transport energy demand module, this aggregate demand structure is complemented by the endogenous representation of transport energy demand described in Sect. 2.4.1.

2.3.2 Climate impacts on wind power availability

Climate change is expected to have an impact on wind energy generation, mainly through changes in extreme events. Instead of uniform reductions or increases in average wind speeds, projections indicate increased variability, including more frequent, longer lasting and intense periods of low wind episodes (Zheng et al., 2024). These episodes can significantly affect system reliability and electricity market prices, especially in electricity systems with a high share of variable renewable energy (Gonçalves et al., 2024). Given FRIDA's global model boundary, these effects are represented through estimated changes in Full Load Hours (FLH) at the global level to capture the impacts of climate change on energy production.

FRIDA v2.1 represented wind availability using a constant number of annual FLH. This assumption disconnects wind generation from climatic changes produced endogenously by the model. FRIDA v3.1 therefore introduces a temperature-dependent adjustment to FLH, representing the effects of climate variability on the wind production.

Using the global temperature and synthesis wind speed trends reported in Fei et al., (2023) for 1989–2021, FRIDA v3.1 approximates the change in global mean wind speed as 0.058 m/s per °C of STA. Given the dependence of wind power output on wind speed, the resulting wind-speed anomaly modifies the annual FLH of wind turbines. However, changes in mean wind speed alone do not adequately capture the potential impacts of climate change on wind power generation. The frequency distribution of wind speeds is also expected to change, with relevance for periods of exceptionally low wind availability (Qu



et al., 2025). FRIDA v3.1 therefore represents the effects of changes in the frequency and duration of extremely low wind power events through reduced-form relationships with STA. Frequency is defined as the number of hours with a capacity factor (CF) below 0.1, whereas duration refers to the hourly CFs below the 20th percentile of the 1980-2022 climatic period. The resulting frequency and duration effects are combined to estimate associated changes in annual FLH. Annual wind-energy FLH therefore reflects the balance between climate-driven changes in average wind conditions on annual FLH and the potential losses associated with increasingly frequent or persistent low-wind events on wind power availability.

2.4 Behavioural Change module

FRIDA v3.1 extends the Behavioural Change module to represent transport energy demand and fertilizer use as endogenous outcomes of interacting behavioural, economic, technological, and resource conditions. Both applications adapt the behavioural change modelling framework previously developed for food and animal-product demand in FRIDA v2.1 (Rajah et al., 2025). The framework distinguishes among three main drivers of demand: a descriptive norm formed from recent changes in behaviour, a personal norm reflecting the perceived desirability and consequences of consumption, and perceived accessibility reflecting the conditions that enable or constrain consumption. Their relative influence changes with economic development, allowing behaviour to shift from being predominantly accessibility-constrained toward being increasingly shaped by normative considerations (Rajah et al., 2025).

Although transport energy demand and fertilizer share this general structure, the processes informing their behavioural drivers differ. Transport energy demand responds to recent consumption, economic conditions, energy costs, the composition of energy supply, and perceived health and environmental consequences. Fertilizer demand is additionally conditioned by agronomic limits, market scarcity, and the cost and availability of natural-gas feedstocks. The resulting demand trajectories enter the Energy and Land Use and Agriculture modules, respectively, allowing changes in behavioural driver to propagate through the wider coupled system.

2.4.1 Transport energy demand

FRIDA v2.1 represented global energy demand through a reduced-form logarithmic regression driven by GDP. Following the sectoral disaggregation of energy demand in FRIDA v3.1, this formulation is replaced for the transport sector by an endogenous behavioural submodule consistent with the broader framework developed by Rajah et al. (2025). This change shifts transport energy demand from an externally imposed macroeconomic relationship to a dynamic outcome emerging from behavioural, economic, and technological feedbacks within the model.

The descriptive norm captures expectations formed from recent transport energy use. Perceived demand is extrapolated from recent trends, allowing sustained periods of increasing consumption to reinforce expectations of continued growth, while persistent reductions generate the opposite effect. Through this mechanism, recent behaviour, subsequently considered normal or expected, influences future demand trajectories and creates path dependency in transport energy consumption. Perceived



accessibility, by contrast, represents the economic conditions enabling transport energy use. Accessibility depends on a combination of income and cost of energy, allowing demand to expand when transport energy becomes more affordable and to contract when economic conditions become more restrictive.

The personal norm reflects the perceived desirability of transport energy use and is influenced by factors associated with both energy services and their environmental consequences. A key component is the perceived health risk associated with exposure to particulate emissions from energy consumption. Higher levels of exposure increase perceived risk and reduce the attractiveness of transport energy use, particularly in systems with a large dependence on fossil fuels. Empirical evidence suggests that health concerns associated with air pollution can affect transport-related energy consumption and behavioural choices (Wang et al., 2019). As perceived health impacts rise, the normative motivation to consume energy for transportation is reduced. At the same time, the technological composition of the energy mix affects how consumers perceive the environmental and social acceptability of energy use. Previous studies have demonstrated that cleaner energy systems can support higher levels of energy utilization by reducing environmental externalities and improving the sustainability of consumption patterns (Raihan et al., 2025). As the share of renewable energy increases and the energy system becomes cleaner, transport energy becomes less emissions-intensive, increasing its perceived environmental and social acceptability. This strengthens the personal norm and creates a countervailing influence on demand.

Through the interaction of these drivers, transport energy demand emerges endogenously from evolving socio-economic and energy-system conditions rather than being prescribed through an external demand function. Rising particulate pollution can reduce transport energy demand by increasing perceived health risks, while declining emissions and a growing share of renewable energy can promote demand by reducing environmental concerns. Because these effects are represented as feedback processes rather than fixed assumptions, transport energy demand responds dynamically to changes elsewhere in the model.

2.4.2 Fertilizer demand

In FRIDA v2.1, fertilizer use was represented through a simplified formulation based on the supply-demand balance of crop and livestock production. In FRIDA v3.1, this formulation is replaced by the Fertilizer Demand submodule based on the behavioural change framework developed by Rajah et al. (2025). This change shifts fertilizer use from a technical input determined primarily by agricultural production requirements to a dynamic outcome emerging from behavioural, economic, agronomic, and resource conditions.

The descriptive norm captures expectations formed from recent experience. Farmers extrapolate the recent trajectory of fertilizer use by projecting the short-term trend in perceived consumption over a one-year expectation horizon. Consequently, sustained increases in fertilizer use reinforce expectations of future increases, while persistent declines generate the opposite effect. Through this mechanism, recent behaviour exerts a reinforcing influence on future demand.



The personal norm is shaped by two perceptions: the perceived social value of fertilizer use and perceived consumption risk. The perceived social value adjusts gradually toward an indicated value determined by fertilizer use relative to its long-term historical average. Persistent increases in use therefore strengthen the perceived normality and desirability of fertilizer application, whereas prolonged reductions weaken it. Perceived consumption risk provides an opposing influence. Fertilizer use is evaluated relative to a maximum agronomically useful application level, defined as global cropland area multiplied by a maximum useful nitrogen application rate derived from FAO country-level fertilizer application data. When fertilizer use exceeds this threshold, the resulting over-application is interpreted, following a perception delay, as evidence of diminishing returns and increasing environmental costs. This perceived risk enters the personal norm with a negative sensitivity, progressively reducing the behavioural motivation for further fertilizer use. Unlike the food-demand applications of the framework (Rajah et al., 2025), climate-risk perception is not included as a driver because there is no clear theoretical basis for assuming a direct positive or negative relationship between climate-risk perception and fertilizer-use decisions. Instead, perceived consumption risk acts as the principal balancing feedback on fertilizer demand.

Perceived accessibility represents the economic and systemic factors that enable or constrain fertilizer use at the global scale. Accessibility is calculated as a multiplicative modification of a reference fertilizer demand and consists of four effects: an income effect, a market scarcity effect, a fertilizer feedstock cost effect, and a physical feedstock availability effect. The income effect depends on GDP per capita through a calibrated elasticity. The scarcity effect is derived from the divergence between short-term and long-term growth rates in fertilizer demand and serves as a proxy for supplier forecasting error and resulting market tightness. Together, these effects capture changing economic conditions influencing fertilizer availability and affordability.

The feedstock cost and availability effects introduce a direct coupling between fertilizer demand and the Energy module. Nitrogen fertilizer production is assumed to depend primarily on natural gas, reflecting conventional ammonia production via steam methane reforming. Fertilizer feedstock costs are determined endogenously from natural-gas extraction productivity, scaled by the stoichiometric carbon requirement for ammonia production and by an energy factor, representing natural gas used both as chemical feedstock and as process fuel. This formulation approximates conventional ammonia production systems in which roughly two-thirds of natural-gas inputs are consumed as feedstock and one-third as process energy. The resulting feedstock cost influences accessibility through a calibrated price elasticity and is further scaled by the share of total nutrient supply provided by synthetic fertilizer, ensuring that price signals affect only the manufactured component of fertilizer use. Physical feedstock availability is represented by comparing the natural gas required for fertilizer production with total natural-gas extraction. As fertilizer production claims a larger share of available gas resources, perceived accessibility declines, reducing the demand that can be realized. Through these mechanisms, changes in fossil-fuel productivity, energy prices, and resource availability propagate endogenously into the agricultural system and influence fertilizer-use decisions.



This structure enables fertilizer demand to emerge from interacting behavioural, economic, and resource constraints rather than from externally imposed assumptions. Consequently, fertilizer use is regulated through internal reinforcing and balancing feedbacks rather than through exogenous caps. This structure implies that an energy transition that moves away from natural gas reduces perceived accessibility, weakening the behavioural motivation to apply fertilizers and ultimately lowering demand. This decline emerges entirely from the interaction between energy-market dynamics and the behavioural decision framework, demonstrating the capacity of the submodule to generate realistic demand trajectories from structural feedback processes alone.

2.5 Resources module

2.5.1 CCS and CDR deployment

FRIDA v3.1 introduces a new representation of CCS and CDR within the Resources module. The structure represents the introduction and development of CCS/CDR systems, simulating public policies that would encourage greater private investment in these new technologies, their impact on the economy and the energy transition and, above all, their impact on greenhouse gas emissions and the climate. It interacts directly with the Climate, Energy, Economy, and Land Use and Agriculture modules. The Government Regulations module, containing exogenous policy inputs, sets the target CO₂ capture rates.

Three distinct technologies and capture routes are represented, each corresponding to a different source of emissions. End-of-pipe carbon capture (EOPC) removes CO₂ directly from emissions produced by fossil fuel use, including coal, oil, and natural gas. Bioenergy with carbon capture and storage (BECCS) captures emissions from bioenergy production, producing net removal of CO₂ from the atmosphere because the carbon absorbed during biomass growth is later captured and permanently stored. Direct air carbon capture (DACC) removes CO₂ directly from the atmosphere each year. Each route is subject to different emission sources, capacity requirements, costs, and resource constraints.

Given that many sources are dispersed or technically inaccessible for capture infrastructure (Bui et al., 2018), FRIDA v3.1 assumes that only a portion of emissions can be captured: 90% of coal emissions, 50% of gas emissions, and 10% of oil emissions (Energy Transitions Commission, 2022; International Energy Agency, 2023), reflecting differences in how these fuels are used. For biofuel processing, 56% of emissions are assumed to be capturable (Fajardy et al., 2019). In addition, BECCS deployment is constrained by biomass availability from the Land Use and Agriculture module, connecting its expansion to competition among bioenergy, food, and feed production.

Desired deployment can be generated either through regulated capture requirements set externally or through an endogenous economic choice. External policy can specify the minimum shares for emissions from coal, oil, and natural gas, biofuel processing, while a separate target (expressed as a share of the atmospheric CO₂ anomaly since 1750) determines the desired removal rate through DACC. In the endogenous formulation, set up as the default, the share of emissions routed to storage is derived rather than imposed: the marginal carbon content of additional energy production is allocated between paying the CO₂



60 emissions tax and paying for capture and storage, with allocation priorities set by the inverse of each option's marginal cost per tonne. Higher carbon prices, lower capture and storage costs, or a larger public contribution to those costs increase the share of emissions directed toward storage. The desired capture share is therefore the larger of this endogenous economic choice and any regulated minimum, subject to the technology-specific capturable shares.

Desired deployment does not immediately translate into realized capture. For each route, the gap between desired and installed
65 capacity determines the desired additional capacity sought over a ten-year construction period. The corresponding investment requirement is calculated from the desired capacity and its unit installation cost. DACC also requires investment in the energy capacity needed to operate the removal process, causing its deployment to compete for both capital and energy-sector investment. Total CCS and CDR investment is further constrained by a user-defined maximum share of real private investment (to prevent inadvertent user-driven, CCS-caused economic depressions). Where available investment is insufficient, funding
70 is allocated first to storage costs and the remaining investment is distributed proportionally among the capture routes. Realized investment increases installed capacity, which subsequently depreciates over time.

In all cases, capture and storage costs evolve endogenously as technologies are deployed. Unit costs decline toward technology-specific floors as cumulative installed capacity increases – i.e., learning by doing (McDonald and Schrattenholzer, 2001). Rapid expansion is penalized via a stepping-on-toes effect representing the bottlenecks of scaling supply chains or qualified
75 injection sites. Storage costs carry an additional resource depletion term that rises with cumulative injected CO₂ relative to a global storage resource base, so that cheap reservoirs are exhausted first (Rogner, 1997). Actual capture in any year is limited by both installed capacity, and the capturable emissions available to relevant capture route. Captured CO₂ accumulates in a stored-CO₂ stock, from which any portion whose storage cost cannot be afforded in that year returns to the atmosphere as leakage. Finally, the share of storage cost not covered by government is added to the marginal cost of delivered fossil energy,
80 and total CCS outlays are tracked as a share of GDP and split between public and private sources, so that the pace and extent of CCS expansion, and its contribution to emissions reduction, are conditioned throughout by the wider energy–economy–climate system.

These connections also impose route-specific limitations to deployment. BECCS competes with food and feed production for biomass and land (Köberle, 2019), while DACC competes with other technologies for energy-system investment. EOPC
85 remains limited by the share of fossil-fuel emissions that is technically accessible. Consequently, FRIDA does not prescribe a predetermined deployment trajectory. The timing and scale of deployment emerge from the interaction of climate policy, relative costs, investment constraints, technological learning, energy requirements, biomass availability, and storage resources.



2.6 Demographics modules

2.6.1 Life expectancy

90 FRIDA v3.1 introduces life expectancy at birth as an indicator within the Demographics module. This indicator represents the
 global average expected lifespan of a given population cohort exposed to the age-specific mortality rates in that year, from
 birth to death. It therefore provides a measure of mortality conditions rather than a prediction of the realized lifespan of a
 cohort born in that year. Life expectancy at birth is computed directly from the age-specific mortality rates already represented
 in FRIDA v2.1. Following Cunningham et al. (2008), the metric is approximated by summing the probabilities of surviving
 95 from birth to each successive age and adding 0.5 years. The additional half-year reflects the assumption that deaths are
 distributed uniformly within each year of age. Since the mortality rate for those aged above 100 is not specified in FRIDA, the
 calculation of life expectancy assumes that the probability of reaching ages over 100 is zero. The resulting truncation of the
 survival distribution at age 100 produces a downward bias in calculated life expectancy equal to the expected years lived
 beyond age 100. This effect is small when survival to age 100 is rare, but may become more consequential in future scenarios
 00 in which mortality rates decline substantially and a larger share of the population would otherwise survive beyond 100.
 Accordingly, projections approaching this upper-age boundary should be interpreted as conservative estimates of life
 expectancy rather than as representing changes in mortality above age 100. This simplification does not meaningfully affect
 the model's ability to reproduce the historical trajectory of global life expectancy, as shown by the comparison with data from
 the United Nations Department of Economic and Social Affairs, Population Division (2024) in Fig. 2c of Sect. 3.

05 Life expectancy is an indicator derived from the model's endogenous mortality structure and therefore does not drive
 demographic change. Age-specific mortality rates, and thus life expectancy, are responds to GDP per person (higher GDP per
 person leads to higher life expectancy) as well as climate damages from sea level rise (i.e., flooding) and rising temperatures
 (more climate damages leads to lower life expectancy). Life expectancy consequently provides a summary measure through
 which the combined implications of socioeconomic development and climate damages for population health can be examined.

10 2.7 Economy module

FRIDA v2.1 represents the economy as an endogenous, feedback-rich climate–economy system from which a persistent
 climate-driven financial default dynamic can emerge (Schoenberg and Callegari, 2025). As climate damage accumulates, firms'
 assets and profitability deteriorate, increasing loan failures and defaults (Dafermos et al., 2018). Banks respond by tightening
 lending standards. Since this response does not fix the underlying climate issue, the declining rate of credit creation eventually
 15 constrains the investments required for climate adaptation and mitigation plans, leaving the economy more exposed to further
 climate damages.

In FRIDA v3.1, we explore two sets of policy structures aimed at supporting investment under conditions of climate-driven
 financial instability: credit insurance and public investments. Credit insurance aims to mitigate financial losses, supporting



private investments in the process, while public investment policies aim to replace the weakening private investments. Due to FRIDA's globally aggregated macroeconomic structure, these policies are not designed as particular country-specific programmes, but rather as exploratory system-level experiments meant to reveal how climate-finance default dynamics respond to different policy interventions, and to explore the costs and consequences of different potential policy instruments.

2.7.1 Credit insurance policy

Credit insurance is modelled as a macro-financial risk-sharing mechanism. The banking sector pays regular premiums to the insurer. The insurer absorbs a fraction of climate-caused risky defaults. These insured defaults do not affect lending standards. By partially absorbing this default signal, insurance eases credit tightening and helps sustain investment (Altunbas et al., 2024; Collier, 2020; Hermann et al., 2016). Regular defaults and therefore regular credit risks dynamics remain unaffected.

The credit insurance policy comes in three variants, depending on how the instrument is funded: private insurance, central bank insurance and public insurance. Private insurance is designed as a compulsory insurance mechanism paid by their primary beneficiary: the banking sector. Insurance reserves are built through premiums paid by the banking sector. When payouts exceed premium income, the reserve declines and a years-of-coverage signal raises premiums to rebuild it. Conversely, when reserves exceed their target, premiums are adjusted downwards. This endogenous solvency feedback mechanism prevents private insurance from operating as unlimited source of external funding (Collier, 2020; Hermann et al., 2016). Central-bank insurance works as a monetary backstop: a percentage of loans impaired by climate damages are swapped for central bank deposits (Skinner, 2021; Svartzman et al., 2021). Solvency is strengthened without charging premiums or taxation. While there is no pre-funding constraint, this intervention introduces an inflation and interest-rate trade-off (Taylor, 1993). Public insurance operates as a fiscal risk-sharing mechanism, funded through endogenous taxation. If tax revenue falls short of payouts, the gap is temporarily covered by additional public debt, raising the debt-to-GDP ratio (Agarwala et al., 2021; Lamperti et al., 2019). However, the insurance tax rate is itself set by a reserve-gap feedback controller that raises the rate when the diagnostic government insurance reserve runs below its target and eases it when the reserve is comfortable, thus limiting additional public debt issuance to emergency situations.

The percentage of climate-related bankruptcies covered by insurance can be adjusted over time, and the three funding sources can be used individually or in combination. The institutional variants feed back differently through the banking system: the private insurance premiums are bank liabilities, central-bank insurance-related deposits are bank assets, and unfunded government payouts increase public debt. Insurance therefore affects both lending decisions and the distribution of financial exposure across private and public balance sheets.



2.7.2 Public investment policy

Public investment is introduced as a complementary lever that works directly on the investment side of the loop, supporting credit, economic growth, and employment (Corrocher and Cappa, 2020; Cullison, 1993). The policy comes into two variants, depending again on the funding source, namely the fiscal or monetary authorities.

The public investments policy intervenes after credit conditions have constrained private investment. Rather than reducing the measured default signal, they add investment expenditure directly to firms' cash inflows and production activity. The additional investments also generate desired hiring in the Employment submodule, so the intervention propagates through employment, wages, household income, demand, and GDP. Public investments, thus, compensate for some of the consequences of insufficient private investment, but do not remove either the original climate-caused defaults or the banks' incentive to tighten credit.

Government-led public investment is represented as a policy stock that adjusts toward a target each year. The target depends on the gap between a desired growth rate and last year's real GDP growth, scaled by nominal GDP. This is a proportional controller that expands investment when growth falls short and eases as growth recovers. The policy is financed through taxation, with the burden split across profits, rents, wages, and wealth taxes according to dedicated policy levers. If taxation is insufficient, additional public debt is issued to finance the policy. The resulting investments flow into the firms' accounts, increasing hiring in the Employment module. This policy captures the trade-off between additional investments and additional taxation (Buffie et al., 2012; OECD, 2016). Tax rates approach their targets gradually rather than changing instantaneously, while any residual financing requirement is added to government debt. This creates endogenous distributional and fiscal effects because profits, rents, wages, and wealth taxation affect firms, workers, and asset owners differently, and debt financing raises future interest expenses.

Central bank-led public investment is represented by a counter-cyclical investment target. The target rises when growth falls below its smoothed long-run trend and recedes when growth runs above it, so the central bank invests more in weak years and less in strong ones. The central bank lending to the corporate sector is indirect, mediated by the private banking system. The central bank issues new deposits for the private banks, which in exchange issue new deposits for the private firms. The central bank is compensated with private firm loans. The private firms pay interest on their loans, deflating both private and central bank deposits in the process. The increased investments lead to increased production and hiring. The attending monetary expansion can add inflationary and interest-rate pressure. This stylized structure extends the literature on central banks acting beyond their conventional mandates to support investment and financial stability under climate risk (Svartzman et al., 2021).

3 Endogenous Model Behaviour

To evaluate the behavioural implications of the structural changes introduced in FRIDA v3.1 as outlined above, we first assess the model's ability to reproduce observed historical behaviour and then apply the same Endogenous Model Behaviour (EMB)



scenario design used for FRIDA v2.1 (Schoenberg et al., 2025). The EMB scenario represents a baseline future in which no additional climate mitigation, adaptation, or socio-economic policies are imposed beyond those already implied via calibration. Rather than prescribing externally defined development pathways, future trajectories emerge endogenously from the interactions within and between the coupled human and climate systems. Each simulation therefore reflects a unique but internally consistent realization of the feedback processes represented within FRIDA.

The model is calibrated against historical observations spanning the period 1980-2023 using a partial-calibration approach in which individual modules are calibrated independently where possible. Calibration minimizes the squared error between observed and simulated behaviour using the BOBYQA optimization algorithm (Powell, 2009) implemented in Stella Architect (Stella Architect, 2025). Published parameter estimates are adopted directly where available, while uncertain parameters are estimated through calibration within literature-derived or expert-defined bounds. Across the model, FRIDA v3.1 is calibrated against 173 historical time series covering climatic, demographic, economic, land-use, agricultural, and energy-system variables. Structural and behavioural validation are performed throughout model development (see Barlas, 1996) to build confidence that model behaviour arises from sufficiently realistic underlying causal mechanisms.

The quality of the calibration is illustrated in Fig. 2, which compares the calibrated model trajectory with historical observations for three of the newly introduced structures: global fertilizer demand, transportation energy demand, and life expectancy at birth. Overall, the calibrated simulation reproduces the observed dynamics of all three variables with good fidelity over the 1980-2023 calibration period. The model captures the long-term increase in global fertilizer use over the calibration period (Fig. 2a). While some local deviations remain, particularly during periods of rapid change, the calibrated trajectory follows the historical trend closely and reproduces the observed increase from approximately 85 Mt N yr⁻¹ in the late 1970s to more than 130 Mt N yr⁻¹ by the early 2020s.

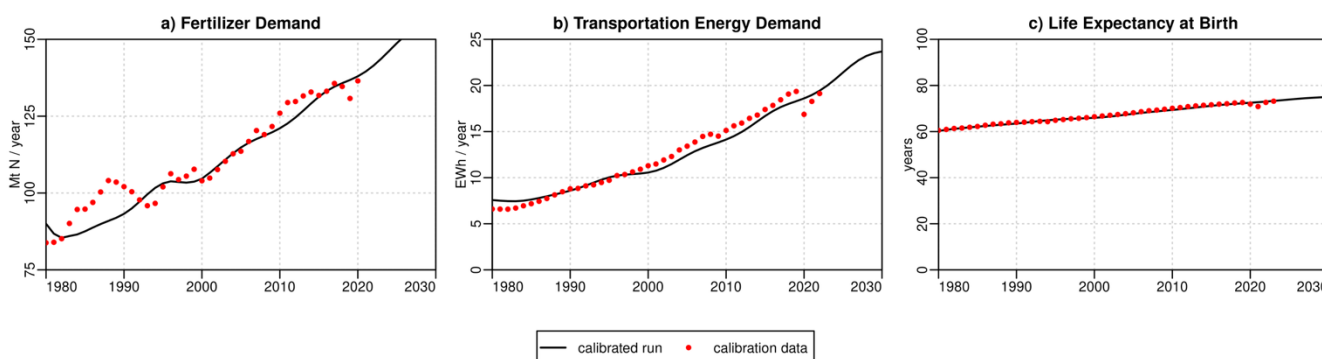


Figure 2. Historical calibration of selected new FRIDA v3.1 structures. Black lines show the calibrated model run and red markers show calibration data. Panels show (a) global nitrogen fertilizer demand, (b) transportation energy demand per person, and (c) life expectancy at birth. The close correspondence between simulations and observations indicates that the



newly introduced behavioural and demographic representations reproduce the dominant historical dynamics over the calibration period.

For transportation energy demand (Fig. 2b), the calibration reproduces the sustained rise in per-capita transport energy consumption observed over recent decades. To reproduce the end-of-series demand levels while accounting for observed disruptions associated with the COVID-19 pandemic, which are not explicitly represented in FRIDA, the calibration shows an underestimation of transportation energy demand during the 2000's and 2010s (Fig. 2b). This trade-off improves agreement with the most recent observation while preserving the overall long-term demand trajectory. Nevertheless, the simulated behaviour remains within reasonable proximity to the historical record and successfully reproduces the dominant long-term trend.

The strongest agreement is observed for life expectancy at birth (Fig. 2c). The calibrated model closely follows the historical increase in global life expectancy from approximately 60 years in 1980 to more than 72 years by the early 2020s. Both the magnitude and timing of the observed changes are reproduced, with exception of the temporary decline associated with the COVID-19 pandemic around 2020-2021.

Fig. 2 therefore demonstrates that the newly introduced fertilizer demand, transport energy demand, and life expectancy structures can reproduce observed historical behaviour while remaining fully embedded within FRIDA's endogenous feedback architecture. The calibration performance provides confidence that these additions generate realistic baseline dynamics prior to their application in future scenario analysis.

Uncertainty is quantified using a global sensitivity analysis consisting of 100,000 ensemble members. In each run, uncertain model parameters are sampled across their plausible ranges using Sobol-sequence sampling, allowing efficient exploration of a high-dimensional parameter space. The sampled parameters encompass uncertainties associated with climate sensitivity, socio-economic development, technological change, human behaviour, climate impacts, and numerous other feedback processes represented within the model. Unlike scenario frameworks such as the SSPs (O'Neill et al., 2014; Riahi et al., 2017), ensemble members do not contain exogenous assumptions concerning future policy changes or time-varying socio-economic pathways (Pirani et al., 2024; Schoenberg et al., 2025). Instead, parameter values remain fixed within each simulation and future trajectories arise entirely from the endogenous evolution of the model structure. The resulting ensemble provides probabilistic bounds around future trajectories and serves as the reference case against which structural modifications can be assessed.

3.1 Comparison with FRIDA v2.1

In this section, we compare the EMB behaviour of FRIDA v3.1 with that of FRIDA v2.1 to evaluate the extent to which the newly introduced structures and changes in FRIDA-Clim calibration modify long-term system behaviour. Despite the addition

of new wildfire climate damages, fertilizer use, sectoral energy-demand disaggregation, endogenous CCS structures, macro-financial policy structures, and the recalibration of FRIDA-Clim, the overall behaviour of the coupled system remains broadly consistent with FRIDA v2.1. At the aggregate level, both model versions produce overlapping magnitudes and trajectories for global temperature (Fig. 3a), economic development (Fig. 3b), population (Fig. 3c), and energy demand (Fig. 3g), indicating that the new processes do not fundamentally alter the model's characterization of baseline human-climate co-evolution. Likewise, there are noticeable but small changes in land-use allocation due to the changes in the FRIDA-Clim calibration, and calibration data sources, as well as the significant changes to fertilizer use (Fig. 3h), and the associated feedbacks that connect agriculture, energy markets, and climate impacts.

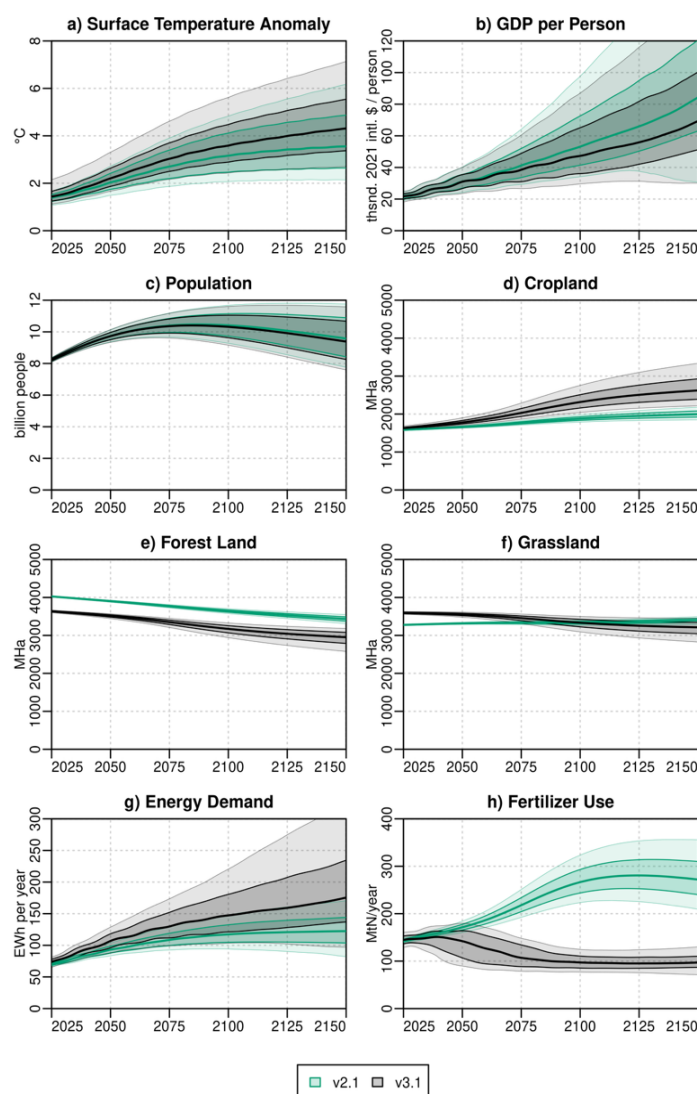




Figure 3. Comparison of Endogenous Model Behaviour (EMB) ensembles from FRIDA v2.1 (green) and FRIDA v3.1 (black) for (a) surface temperature anomaly, (b) GDP per person, (c) population, (d) cropland area, (e) forest land area, (f) grassland area, (g) total energy demand, and (h) nitrogen fertilizer use. Solid lines represent ensemble medians. Shaded regions indicate ranges containing 67% and 95% of outcomes of the respective 100,000-member ensembles. The EMB scenario represents a

45 *baseline future without additional policy interventions, in which model behaviour emerges endogenously from interactions among the coupled climate, economic, demographic, land-use, and energy systems. Relative to FRIDA v2.1, FRIDA v3.1 produces only minor changes in aggregate climate, economic, population, and energy trajectories, while exhibiting larger differences in fertilizer demand and land-use allocation due to the introduction of endogenous fertilizer-use dynamics, climate-driven wildfire impacts, and revised agricultural feedbacks.*

50 The largest divergence between model versions occurs within the land-use and agricultural system. The changes in the starting levels of land use are the effect of changing the source of calibration data (see Sect. 2.1) in order to be consistent across the calibration of the climate component and the full IAM. Relative to v2.1, FRIDA v3.1 projects substantially greater future cropland expansion (Fig. 3d), reaching approximately 2.3 billion hectares by 2100 compared with roughly 1.9 billion hectares in v2.1, due primarily to changes in fertilizer use. This increase is accompanied by a corresponding reduction in

55 forest area (Fig. 3e) and grassland area (Fig. 3f), which specifically declines more rapidly throughout the century. By 2100, the median grassland area falls below the relatively stable trajectory simulated in v2.1. These differences arise primarily from the introduction of endogenous fertilizer-use dynamics, and to a much smaller extent the new wildfire dynamics which alter land productivity, carbon cycling, and agricultural adjustment processes.

The new fertilizer use representation generates the most pronounced behavioural change among all newly introduced

60 structures. In FRIDA v2.1, fertilizer demand continued to increase throughout the century as a function of production requirements. In contrast, the endogenous behavioural formulation in v3.1 produces a peak around the middle of the century followed by a sustained decline, reaching 90–100 Mt N yr⁻¹ by 2100 (Fig. 2h). This decrease emerges from interactions between fertilizer accessibility and social-behavioural responses, but is driven primarily by rising natural gas energy feedstock costs due to the energy transition having taken place, reducing the use of natural gas, creating a self-limiting

65 feedback in fertilizer use that was absent from FRIDA v2.1. The resulting reduction in fertilizer use contributes to lower cropland productivity growth, requiring additional cropland expansion to satisfy agricultural demand and thereby driving the observed land-use shifts.

Changes in the energy system are comparatively modest. Median global energy demand (Fig. 3g) is higher in v3.1 than in v2.1, particularly after 2050, reflecting the inclusion of sectoral demand dynamics and the behavioural structure driving

70 transport energy demand. However, uncertainty ranges contain significant overlap between the two models, indicating that the new energy-demand structure modifies system behaviour without fundamentally altering long-run energy trajectories.



Similarly, population projections (Fig. 3c) remain nearly unchanged, with both versions producing peak global populations close to 10–11 billion people during the late twenty-first century.

These sectoral changes propagate into the climate-economy system but produce moderate aggregate effects. FRIDA v3.1 generates marginally lower median GDP per person and a higher surface temperature anomaly than v2.1 by the end of the century. The temperature difference is on the order of a few tenths of a degree Celsius, driven primarily by changes in the FRIDA-Clim calibration (see Sect. 2.1), while GDP per person outcomes are lower, likely in part due to that increased warming, though with substantial overlap across ensemble ranges.

Overall, the comparison demonstrates that FRIDA v3.1 preserves the broad characteristics of the EMB scenario identified in Schoenberg et al. (2025), including continued global warming, slower economic growth than found in the SSP baseline scenarios, stabilization of global population growth, and persistent pressure on land resources. The newly introduced structures primarily refine the internal mechanisms generating these outcomes rather than fundamentally changing them. Consequently, the transition from v2.1 to v3.1 can be characterized as an incremental extension of the model's feedback architecture, with notable effects concentrated in agriculture and land use, with smaller changes to aggregate climate and socio-economic trajectories.

3.2 New Concepts in FRIDA v3.1

To illustrate the behaviour of the structures introduced in FRIDA v3.1, we examine the EMB ensemble trajectories of four new indicators introduced in this update of the model: climate-driven burned area, transport energy demand, wind energy FLH, and life expectancy at birth. Together, they demonstrate how the new structures evolve endogenously through interactions among the climate, energy, economic, and demographic subsystems. Fig. 4 presents the EMB ensemble results for these four indicators. While each indicator exhibits substantial uncertainty, all display distinct long-term behavioural patterns that emerge from the newly introduced feedback structures rather than from externally prescribed assumptions.

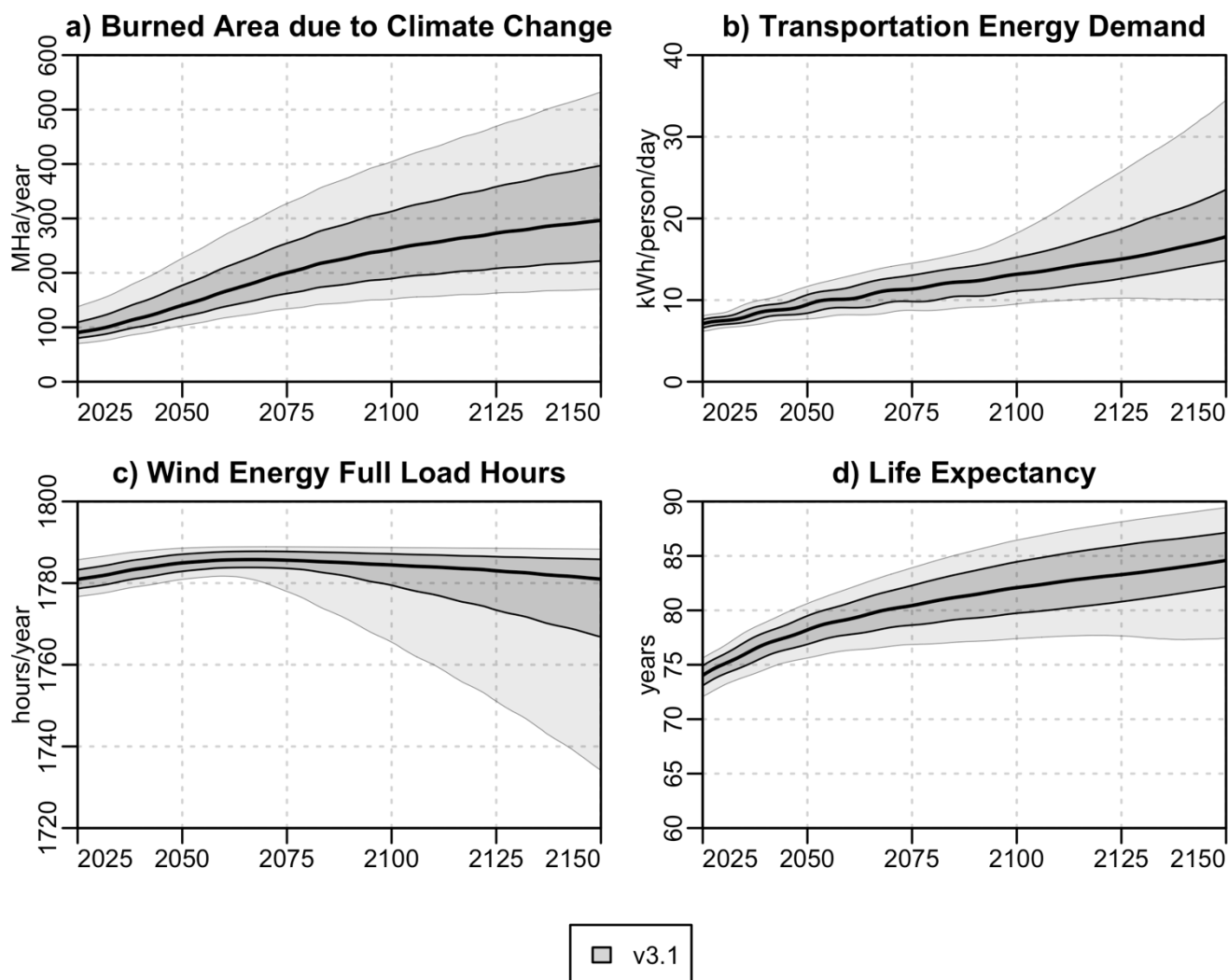


Figure 4: Ensemble projections from FRIDA v3.1 for (a) climate change-induced burned area, (b) transportation energy demand, (c) wind energy full-load hours, and (d) life expectancy. Solid black lines represent ensemble medians. Shaded regions indicate ranges containing 67% and 95% of outcomes from the 100,000-member ensemble. Results suggest increasing wildfire activity and transportation energy demand throughout the twenty-first century, continued improvements in global life expectancy, and relatively stable wind energy resource quality with growing uncertainty toward the end of the century. The widening uncertainty ranges reflect the propagation of uncertainties associated with climate sensitivity, socioeconomic development, technological change, behavioural responses, and other interacting feedback processes represented within FRIDA.



Climate-driven burned area increases steadily throughout the simulation period (Fig. 4a), reflecting the positive relationship between global mean STA and the fraction of burned area attributable to anthropogenic climate change. Median climate-driven burned area reaches more than 200 Mha by 2150, representing a tenfold increase relative to the historical baseline used to parameterize the wildfire module. Growth is initially moderate during the first half of the century but accelerates as warming intensifies, before gradually slowing toward the end of the simulation as temperature trajectories and the underlying burned-area response begin to saturate. Uncertainty increases substantially over time, with the interval containing 95% of the results widening significantly through 2150. This expanding range reflects differences in future temperature pathways across ensemble members, which are amplified through the nonlinear STA-burned area relationship and propagated through the wildfire impact structure

Transport energy demand per person increases steadily throughout the simulation period, reflecting continued economic growth and the endogenous behavioural processes represented in the transport-demand module (Fig. 4b). Historical observations are reproduced well during the calibration period, after which median per capita transport energy demand rises over the simulation horizon. Growth is strongest between approximately 2030 and 2080, coinciding with sustained increases in GDP per person. Although climate-related personal norms, and health risks initially exert downward pressure on transport energy demand through the behavioural framework, this effect gradually weakens as the energy system transitions toward lower-emission energy sources. As a result, both reductions in exposure to transport-related air pollution, and the lessened impact of marginal changes in demand on climate change, diminish the influence strength of the feedback processes that would normally suppress demand, allowing transport energy consumption per person to continue increasing. After the late twenty-first century, demand growth moderates as economic growth slows, leading to a gradual tendency toward stabilization rather than continued acceleration. Uncertainty increases substantially over time, with the range encompassing 95% of the ensemble members widening markedly after mid-century, indicating that differences in socio-economic development, technological change, and behavioural responses generate increasingly divergent long-term transport energy pathways.

Wind energy full load hours exhibit only modest changes over the simulation period (Fig. 4c). Median full load hours increase slightly from 1,770 h yr⁻¹ in the historical period to a peak of around 1,785 h yr⁻¹ during the middle of the century before declining gradually thereafter. Overall, the magnitude of change remains small, with median values staying within 1% of the initial level throughout the simulation. The behaviour reflects the balance between modest gains associated with changing average wind conditions and losses associated with more frequent low-wind events. Although uncertainty increases over time, particularly in the lower tail of the distribution, the ensemble median remains relatively stable. These results suggest that the climate-driven effects on global average wind-energy productivity represented in FRIDA are comparatively minor relative to the larger changes observed in other components of the human-climate system.

Life expectancy at birth follows a continued upward trajectory throughout the simulation period (Fig. 4d). The model reproduces the observed historical increase from approximately 60 years in 1980 to more than 72 years by the early 2020s



(COVID-19 notwithstanding) and projects further improvements over the twenty-first and twenty-second centuries. Median life expectancy reaches 80 years around 2070 and approaches 85 years by 2150. The rate of increase gradually slows over time, reflecting diminishing gains as life expectancy reaches higher levels. Some of this slowing may also reflect the model's treatment of survival beyond age 100. Because the life-expectancy calculation assumes zero probability of survival beyond age 100, projected life expectancy is increasingly underestimated as reductions in mortality increase the probability of reaching very old ages. The flattening of the trajectory at high life expectancies should therefore not be interpreted entirely as a modelled limit to further improvements in longevity. Uncertainty widens modestly throughout the projection period, driven by differences across ensemble members in economic development and climate-related mortality impacts. Nevertheless, all central projections indicate continued improvements in longevity, suggesting that the positive effects of rising incomes and living standards outweigh the adverse mortality effects associated with climate change within the EMB scenario.

These results demonstrate the diversity of behaviours generated by the new structures introduced in FRIDA v3.1. Wildfire impacts increase nonlinearly as climate change intensifies, transport energy demand grows with socio-economic development while remaining behaviourally constrained, wind energy productivity exhibits competing positive and negative climate responses, and life expectancy continues to improve despite increasing climate damages. These indicators therefore provide additional insight into the coupled human-climate dynamics represented by FRIDA and illustrate how the new model structures generate insights that were not represented in FRIDA v2.1.

4 Demonstration of Policy Structures

This section demonstrates the behaviour of several new policy mechanisms implemented within FRIDA v3.1 and illustrates how policy interventions interact with the model's coupled climate, financial, and macroeconomic dynamics. The objective is not to evaluate specific real-world policy packages, but to showcase the model's ability to represent a diverse range of policy structures and trace their consequences through multiple economic and environmental pathways.

The first experiment examines the interaction between carbon pricing and its impact on endogenous CCS deployment, demonstrating how mitigation technologies respond to changing economic incentives. The second explores financial and fiscal policy interventions designed to reduce the economic impacts of climate-related financial instability, comparing the private insurance mechanism with a government investment programme. Together, these experiments highlight FRIDA's capacity to represent both climate mitigation policies and economic adaptation measures within a unified modelling framework, while capturing the complex feedbacks that emerge across different sectors of the economy.

4.1 Demonstration of Carbon Capture and Storage with Carbon Taxes

To illustrate the behaviour of the endogenous CCS module introduced in FRIDA v3.1, a set of ensemble simulations was conducted comparing three policy configurations: the EMB baseline, a global carbon tax of US\$100 tCO₂e⁻¹ (2021 dollars)

with endogenous CCS deployment enabled, and an otherwise identical carbon-tax scenario in which CCS is unavailable. The carbon tax is introduced in 2030 and phased in linearly until reaching its full value in 2035. No assumptions are imposed regarding the amount of carbon capture or storage. Instead, firms respond endogenously to the carbon price, choosing whether to pay the tax or deploy CCS based on the relative costs of emissions and carbon storage. As a result, all capture and storage outcomes emerge directly from model dynamics rather than prescribed deployment pathways.

Fig. 5 compares the resulting ensemble trajectories for climate, economic, and CCS-related indicators through 2150. The most immediate effect of the carbon tax is a reduction in long-run warming relative to the EMB baseline. Both carbon-tax scenarios produce a lower STA than the EMB simulation, demonstrating the effectiveness of emissions pricing as a mitigation instrument (Fig. 5a). Differences between the two tax scenarios remain modest during the first several decades because CCS deployment requires time to accumulate. By the second half of the twenty-first century, however, the scenario with endogenous CCS begins to diverge from the equivalent carbon-tax case without CCS, producing consistently lower temperatures. The temperature reduction remains moderate but persists throughout the simulation horizon, indicating that CCS acts primarily as a long-term complement to emissions reductions rather than a short-term substitute.

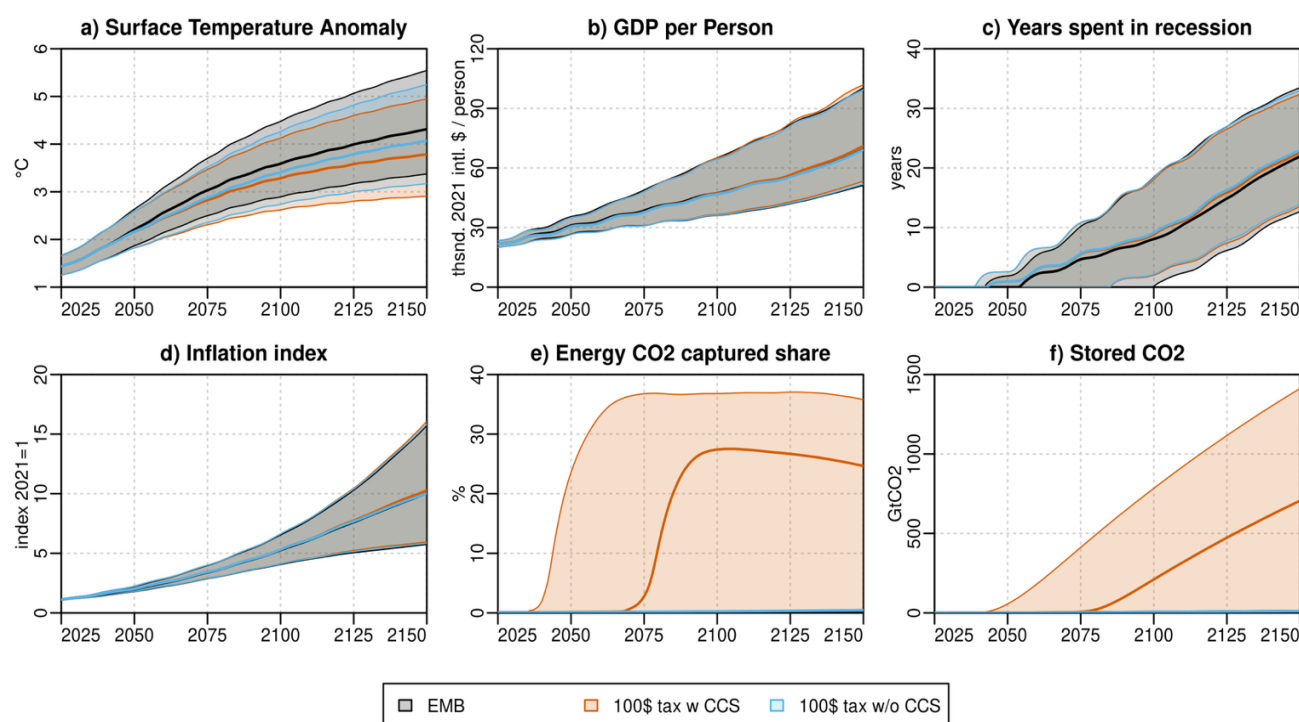


Figure 5. Ensemble projections comparing the EMB baseline, a \$100 carbon tax with endogenous CCS deployment (100\$ tax w CCS), and a \$100 carbon tax without CCS (100\$ tax w/o CCS). Panels show trajectories of (a) surface temperature anomaly



80 (STA), (b) GDP per person, (c) cumulative years spent in recession since 2025, (d) inflation index, (e) energy-sector CO₂
 captured share, and (f) cumulative stored CO₂. Solid lines show ensemble medians. Shaded regions indicate uncertainty
 ranges, with shading containing 67% of ensemble members. Allowing CCS deployment increases the share of energy-sector
 emissions captured and leads to cumulative CO₂ storage. Relative to an equivalent carbon tax without CCS, CCS deployment
 produces lower long-run temperature outcomes while yielding only modest differences in GDP per person, inflation, and
 85 recession incidence across the ensemble.

Economic outcomes differ only slightly between the two carbon-tax scenarios. GDP per person continues to rise throughout
 the simulation period under all three configurations (Fig. 5b). The two carbon-tax pathways track each other closely, with only
 small differences emerging after substantial CCS deployment has occurred. By the end of the simulation, GDP per person in
 the CCS case is marginally higher than in the case without CCS, suggesting that avoided climate damages largely compensate
 90 for the costs associated with constructing and operating capture and storage infrastructure. Relative to the EMB baseline, both
 carbon-tax scenarios exhibit only limited long-run economic penalties.

A similar pattern appears in the macroeconomic stability indicators. The cumulative number of years spent in recession
 increases gradually through time under all scenarios (Fig. 5c). The introduction of a carbon tax produces only a modest increase
 relative to the baseline, and the availability of CCS has little additional effect. Likewise, inflation rises steadily over time in
 95 all scenarios (Fig. 5d). The inflation trajectories under the CCS and non-CCS carbon-tax cases are nearly indistinguishable,
 indicating that endogenous CCS deployment does not substantially alter broader price-level dynamics. Together, these results
 suggest that the CCS module influences climate outcomes much more strongly than conventional macroeconomic indicators.

The operation of the CCS system can be observed directly through the energy-sector CO₂ capture share and cumulative stored
 CO₂ (Fig. 5e-f). In the scenario with endogenous CCS, capture deployment begins shortly after the carbon price is introduced
 00 and increases rapidly during the following decades. The median captured share approaches approximately 20-25% of energy-
 sector emissions by the end of the century before stabilising. No capture occurs in either the EMB baseline or the carbon-tax
 scenario without CCS. The resulting accumulation of stored carbon is substantial. Cumulative storage exceeds several hundred
 gigatonnes of CO₂ during the twenty-first century and continues increasing throughout the simulation period, reaching roughly
 600-700 GtCO₂ by 2150 in the median ensemble trajectory, with substantially larger storage occurring in some ensemble
 05 members (Fig. 5f).

Overall, the experiment demonstrates that endogenous CCS provides an additional mitigation pathway when carbon pricing is
 present. The carbon tax alone reduces warming by discouraging emissions-intensive activities, while the availability of CCS
 enables a portion of remaining emissions to be captured and permanently stored. The resulting climate benefits accumulate
 gradually and become increasingly visible over long time horizons. Importantly, these gains are achieved with only minor
 10 differences in GDP per person, inflation, or recession incidence relative to an equivalent carbon-tax policy without CCS. The



results therefore highlight the value of representing CCS endogenously within an integrated assessment framework, allowing deployment to emerge from economic incentives, infrastructure costs, and storage constraints rather than from externally prescribed assumptions.

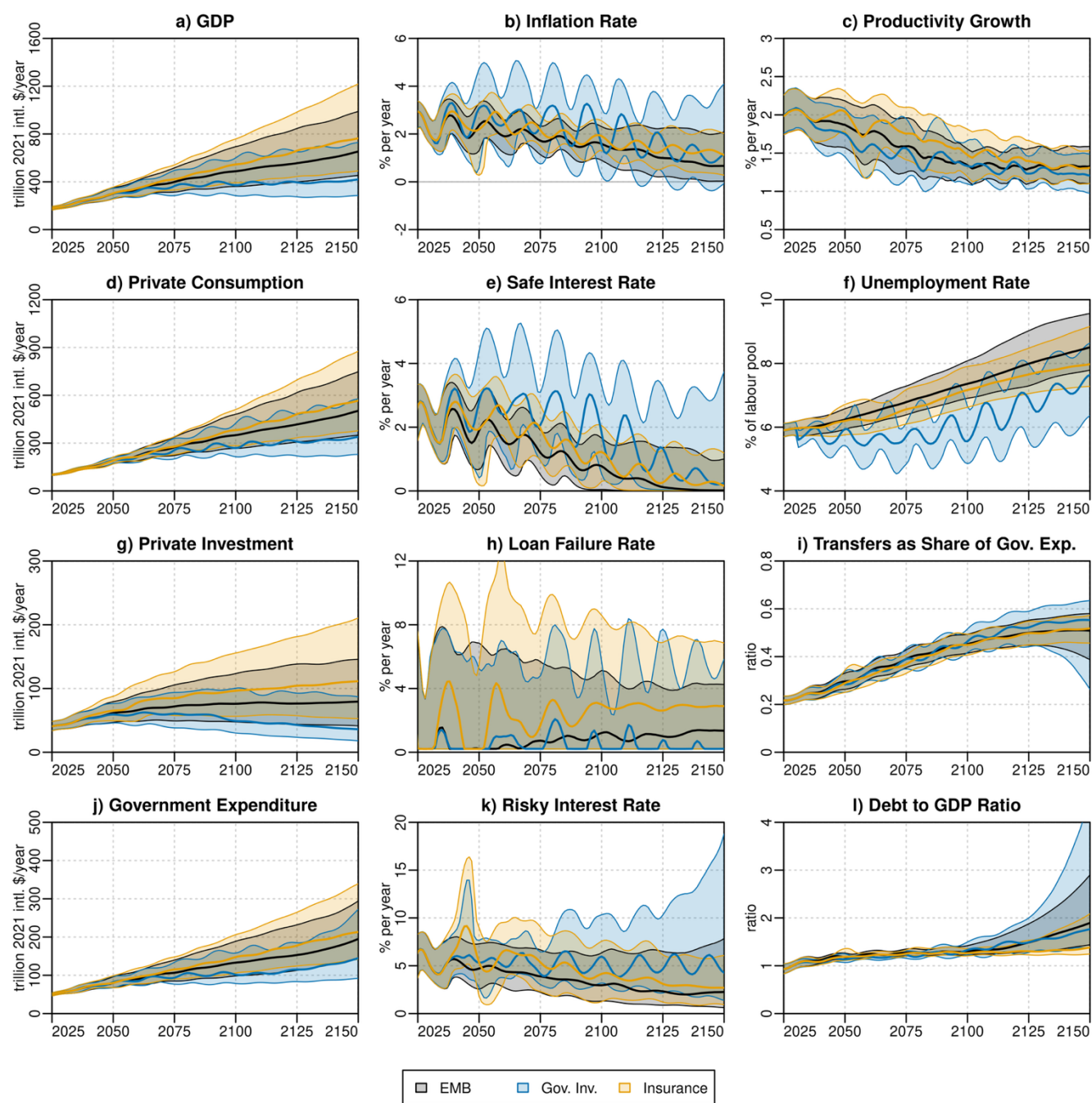
4.2 Demonstration of Insurance & Government Investment Policy

15 Fig. 6 presents the macroeconomic outcomes associated with the insurance and government investment policy scenarios described in Sect 2.7. The insurance policy we test introduces a private insurance mechanism from 2030 onward, gradually increasing coverage to 70% of loans for climate driven defaults over a ten-year implementation period. The government investment policy also begins in 2030 and targets sustained GDP growth by adjusting public investment financed through an equal mix of wage, profits, rents, and wealth taxation. Results are compared against the EMB ensemble discussed in Sect. 3.

20 Both policy interventions are successful in partially counteracting the climate-finance feedback that emerges endogenously in FRIDA, but they do so through different mechanisms and with markedly different macroeconomic consequences. The insurance policy directly reduces the transmission of climate-induced loan failures into lending standards, allowing private credit creation and investment activity to remain stronger than in the EMB scenario. In contrast, the government investment policy does not affect the underlying loan default process and therefore leaves banks' incentives to tighten credit largely intact.
 25 Instead, it compensates for weaker private investment through publicly financed expenditures.

The differences between the two interventions are visible across several macroeconomic indicators. Insurance produces higher GDP trajectories than both the EMB and government investment scenarios throughout the twenty-first century (Fig. 6a). Similar patterns appear for private consumption (Fig. 6d), where the insurance scenario remains above the other cases for the period when the policy is activated. Private investment exhibits a particularly strong divergence between the policies (Fig. 6g).
 30 Insurance supports higher levels of private investment than either the EMB or government investment scenarios following policy implementation, whereas the government investment case in the long term produces a decline in private investment relative to the baseline ensemble. This result reflects crowding out effects.

Opposing responses are also observed for labour productivity growth (Fig. 6c). The insurance scenario maintains productivity growth rates above those of the EMB ensemble for most of the simulation period. The government investment scenario follows
 35 a trajectory below the baseline and insurance cases. The differing patterns are consistent with the distinct channels through which the policies operate. Insurance supports private investment growth, leading to increased exploratory investments. Public investments, on the other hand, focus on expanding demand and employment, leading to slower productivity growth in the long term.



40 *Figure 6. Ensemble projections comparing the Endogenous Model Behaviour (EMB), a scenario with stylized Insurance, and a Government Investment policy experiment. Panels show outcomes for (a) GDP, (b) inflation rate, (c) productivity growth, (d) private consumption, (e) safe interest rate, (f) unemployment rate, (g) private investment, (h) loan failure rate, (i) transfers*



as a share of government expenditure, (j) government expenditure, (k) risky interest rate, and (l) debt-to-GDP ratio. Solid lines show ensemble medians and shaded regions indicate uncertainty ranges (shaded share contains 67% of ensemble members, 95% share not shown to preserve readability). Both policy interventions attempt to mitigate climate-driven financial instability to support long-run economic activity through different mechanisms and with different fiscal and monetary consequences.

The inflation and interest-rate responses further illustrate the distinction between the two policies. Insurance generally supports stronger economic activity while maintaining moderate inflation outcomes, similar to EMB (Fig. 6b). The government investment scenario exhibits higher inflation rates than both the EMB and the insurance scenario throughout much of the century. This reflects the additional demand generated by sustained public investment spending. Because of the impacts on inflation, this drives changes in interest rates, both safe and risky (Fig. 6e and 6k). Higher inflation triggers higher rates consistent with central banks' desire to control the inflationary pressure generated by increased government investment.

The largest contrast between the policies appears in the treatment of financial distress. Unexpectedly, the insurance scenario has increased loan failure rates relative to both EMB and government investment (Fig. 6h), reflecting the increased access to credit and lower overall lending standards supported by the insurance policy. Government investment produces only modest changes in loan failures because it does not alter the underlying exposure of borrowers or the lending decisions of banks. Consequently, the improvement in credit conditions under insurance spreads throughout the broader macroeconomy, whereas government investment primarily acts as a compensatory mechanism after financial stress has already occurred.

One area where government investment outperforms both insurance and the EMB baseline is unemployment (Fig. 6f). Because public expenditures directly generate employment demand and hiring, unemployment remains systematically lower under government investment. Insurance also reduces unemployment indirectly through stronger economic growth, but the effect is smaller because employment gains emerge through market-driven investment decisions rather than direct public job creation. This result highlights an important trade-off between the two interventions: insurance appears to increase aggregate economic performance, whereas public investment is more effective at directly supporting employment outcomes.

The fiscal consequences of the two policies are visible in government expenditure and transfer dynamics. Government investment unexpectedly produces the least public spending (Fig. 6j) because of an overall smaller economy, but that is, accompanied by higher transfers as a share of government expenditure (Fig. 6i). Insurance only has an indirect impact on government activity because of the larger tax base. Despite these differences, neither policy substantially alters long-run debt-to-GDP ratios relative to the EMB ensemble (Fig. 6l), due to the structure of the government sector of the economy in FRIDA which strives to maintain a target debt to GDP ratio, by adjusting non-transfer related government spending.

Overall, Fig. 6 demonstrates that policies targeting the financial transmission mechanism of climate damages can be more effective than policies that attempt to compensate for lost private activity after the fact. The insurance scenario consistently

generates higher GDP, consumption, productivity growth, and private investment while simultaneously reducing loan failures. Government investment succeeds in lowering unemployment and maintaining economic activity during periods of financial stress, but generally underperforms insurance across most macroeconomic indicators because it does not address the underlying deterioration in credit conditions. These results highlight the importance of financial stability as a leverage point within the coupled climate-economy dynamics represented by FRIDA and suggest that preventative risk-sharing mechanisms may provide larger long-run benefits than compensatory fiscal interventions alone.

5 Conclusion

FRIDA v3.1 represents a significant extension of the model's ability to capture feedback between human and climate systems while preserving the endogenous, feedback-based philosophy that underpins the FRIDA framework. The principal developments introduce climate-driven wildfire disturbance, endogenous behavioural representations of fertilizer demand and transport energy demand, sectorally disaggregated final energy demand, endogenous CCS and CDR deployment, and macro-financial policy mechanisms for responding to climate-related financial instability. Supporting developments connect climatic change to wind power availability, update the calibration and selected formulations of the climate and carbon-cycle components, and derive life expectancy from the model's existing age-specific mortality structure. These changes broaden the representation of behavioural responses, climate impacts, mitigation technologies, and financial mechanisms, enabling the exploration of a wider range of socio-environmental dynamics and policy interventions within a single IAM framework.

Evaluation of the updated model indicates that these additions preserve the long-term behaviour established in FRIDA v2.1, while altering the mechanisms through which that behaviour emerges. FRIDA v3.1 reproduces the dominant historical trajectories of fertilizer use, transport energy demand, and life expectancy, and its large uncertainty ensemble produces aggregate climate, demographic, economic, and energy trajectories that broadly overlap with those of the preceding model version. The most pronounced structural consequences occur in the agricultural and land-use system. Endogenous fertilizer demand peaks and subsequently declines as behavioural responses interact with the changing cost and availability of natural-gas feedstocks, reducing productivity growth and increasing pressure for cropland expansion. The remaining additions generate more moderate aggregate changes but establish new pathways through which climate change, technological development, human decision-making, and economic processes interact, providing a stronger basis for analysing uncertainty and evaluating policy responses across multiple sectors. In the EMB scenario, representing a future without additional climate mitigation, adaptation, or socio-economic interventions, these interactions produce warming between 3 and 5.5 °C before 2150, with cascading impacts on ecosystems, agricultural productivity, mortality, and economic output, underscoring the profound systemic risks associated with delayed climate action.

The policy experiments further demonstrate the analytical consequences of representing these processes endogenously. Under carbon pricing, CCS deployment emerges from changing economic and technological conditions rather than following a



- 05 prescribed pathway, producing additional climate benefits as capacity accumulates. The macro-financial experiments show that policy outcomes similarly depend on where intervention acts within the feedback structure: credit insurance limits the transmission of defaults into tighter lending conditions, whereas public investment compensates for the resulting decline private investment. These experiments thus demonstrate the value of closing feedbacks between policy interventions and the conditions governing their implementation.
- 10 Future work will focus on further improving the representation of both energy supply and energy demand. A key priority is the disaggregation of energy supply by carrier, allowing the model to distinguish between electricity, liquid fuels, and gaseous fuels. Such a development would enable a more realistic representation of the global energy transition, while improving the model's capacity to assess decarbonization pathways. A second priority is the continued expansion of the endogenous behavioural framework introduced in FRIDA (Rajah et al., 2025). The behavioural structures currently applied to food, animal
- 15 products, transport energy and fertilizer demand provide a foundation for representing demand as an emergent outcome of economic conditions, technology adoption, social preferences, and policy incentives. Extending this approach to additional end-use sectors, including residential, commercial, and industrial energy demand, would move the model further away from economically driven trajectories and toward a more consistent endogenous representation of human decision-making throughout the global system.
- 20 FRIDA v3.1 thus provides a broader basis for examining how socio-behavioural, technological, biophysical, and financial processes interact within the coupled human–climate system. Further development should extend this analytical capacity without compromising the transparency and computational efficiency required for integrated assessment and policy analysis under deep uncertainty.

Code and data availability. FRIDA is released as a free and open-source model on GitHub (<https://github.com/metno/WorldTransFRIDA>).

- 25 The model code for FRIDA v3.1 is available from <https://zenodo.org/doi/10.5281/zenodo.22916394> (Schoenberg et al., 2026a). The full infrastructure to run the scenario ensembles is hosted on GitHub (<https://github.com/BenjaminBlanz/WorldTransFrida-Uncertainty>). Code and simulation ensemble data for all Figures is available on Zenodo <https://zenodo.org/doi/10.5281/zenodo.22941137> as well as the EMB ensemble data <https://zenodo.org/doi/10.5281/zenodo.22940951>.

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