

# **An endogenous modelling framework of dietary behavioural change in the fully coupled human-climate FRIDA v2.1 model**

Jefferson K. Rajah, Benjamin Blanz, Birgit Kopainsky, and William Schoenberg

## **Response to Referee #1**

### **General comments**

I found this to be a strong paper overall, which significantly furthers research on global integrated assessment modelling. The introduction of a more endogenous food demand model represents a significant improvement over common GDP-based models. The conclusion that current income-driven models may be overestimating future global food demand is a significant, if not expected, finding.

Thank you for taking the time to review our manuscript and for your constructive feedback. Below we provide a point by point response along with the revisions we will make.

The majority of the text is dedicated to model description and presentation of results, with limited reflection or discussion. There could be more emphasis on the relevance of results presented, particularly in relation to the shortcomings of widely available models. Reasons why the endogenous behavioural model predicts lower future food demand when compared to the income-driven model could be discussed more fully.

We dedicated the bulk of the paper to model description and results so as to be within the scope of the GMD's model description paper format. The reviewer's points have been noted, and we have revised some text to strengthen the Conclusions section.

In this paper, we deliberately restricted our comparison of our endogenous modelling approach to the GDP-driven approach within the same base model, FRIDA, to isolate the effect of endogenous dietary behaviours. Comparing our results to other widely available IAMs (e.g. non-endogenous and structurally distinct GCAM) would constitute an apples-to-oranges comparison since the differences in outcomes could stem from differences between base models. Nevertheless, in lines 649-660 of the preprint, we highlight that current models, using GDP-driven modelling approach, could result in overestimated food demand. We also provided an example of tweaks that have been made to mitigate this problem (arbitrary bound + diminishing income elasticities), while arguing that such tweaks do not provide an adequate process-based explanation for behaviour.

We have rephrased some text to bring across our point more strongly, and at the same time reiterate the discussion in the results section for explaining why the endogenous

model predicts lower food demand:

“To evaluate the performance of our endogenous modelling approach, we compared the results of our baseline EMB against the baseline produced by the more common GDP-driven approach. Our findings indicate that while both approaches can acceptably reproduce historical data, our approach results in considerably lower future projections across key human-climate system indicators. As explained in the previous section, our endogenous framework captures how individuals adapt to their changing social-ecological environments such as improved socioeconomic conditions, shifting norms and changing risk perceptions. In response, people may alter their dietary behaviours favourably from a climate mitigation perspective – even in the absence of targeted policies for facilitating pro-environmental behavioural change. We consequently observe relatively cooler future baseline climate projections by endogenizing human behaviour. In contrast to our endogenous behavioural change framework, GDP-driven models assume that human consumption increases proportionally with income, largely ignoring the complex feedback dynamics internal to the human system. Since most IAMs project rising real GDP over the simulation horizon, models using the GDP-driven approach may result in systematically inflated demand projections that do not account for behavioural changes. Such inflated projections feed into the climate system and result in relatively warmer climate futures and potentially overstating mitigation challenges. By demonstrating how complex behavioural feedback can dampen future demand trajectories, our results lend further support to calls for incorporating endogenous behavioural responses into climate modelling and IAMs (e.g., Beckage et al., 2020, 2022).”

Similarly, we strengthened our point that our endogenous modelling approach allows for probabilistic scenario analysis and compare it to existing approaches used by other IAMs:

“Using an uncertainty approach, our simulation results account for a range of plausible behaviours within the 95% confidence bounds. This allows for probabilistic scenario analyses that cannot be achieved with the externally imposed socioeconomic narratives used in the Shared Socioeconomic Pathways (SSP) framework. Several process-based IAMs (e.g., IMAGE, GCAM, MESSAGE-GLOBIOM, REMIND-MAgPIE) use the SSPs to parameterize future scenarios in model runs. While SSPs provide a useful framework for consistency across climate models, such scenarios are non-probabilistic and treat human behaviour as exogenous and static, limiting the ability to capture human-climate feedback dynamics (Beckage et al., 2022). Moreover, while IAMs used for economic optimization (e.g., DICE, MIND, ReMIND) can be run probabilistically, these models do not model human behaviour in a process-based manner. Rather, behavioural outcomes are the result of optimization (typically for cost minimization or utility maximization), which reflect the best possible outcomes achievable under the assumption of full

behavioural control. Consequently, these models do not generate probabilistic scenarios for human behavioural choices or the associated climate outcomes. In contrast, our fully coupled endogenous modelling approach allows us to explore a range of simulated probabilistic futures within a process-based IAM framework without relying on external scenarios nor optimization.”

## Specific grammatical corrections and content suggestions

### Abstract

- The abstract should state that the EBM altered the IAM results by **decreasing** future demand projections, specifically. That is an interesting and important finding
  - Thank you for this suggestion. We have revised the results section of the abstract as such:  
“Our simulation results show that endogenizing human behaviour leads to lower future demand projections compared to the more prevalent GDP-driven modelling approach. This demonstrates the significant impact of behavioural feedbacks on emission behaviours and thus climate outcomes. Importantly, using an uncertainty approach, our results account for a range of plausible behaviours within the 95% confidence bounds, which includes scenarios where we observe reversals of sustainable behavioural change in the future.”

### 1 Introduction

- Line 33: Do you really mean behavioural responses to climate change here, or it is any climate-relevant behaviour, whether or not this behaviour is a direct response to climate change?
  - Beckage et al. (2020) use the term ‘behavioural responses to climate change’ repeatedly. But they also state: “Humans respond dynamically to climate change in a boundedly rational manner, updating beliefs and behavior in response to experiences of climate change, the influence of social networks, and other social, cultural, and political factors” (p.182). Similarly, van Valkengoed et al. (2025) consider both climate impacts and other drivers to underlie lifestyle change (see Figure 2).
  - Given this context, alongside your question, we have revised this line as such:  
“While IPCC authors have emphasized the potential of demand-side mitigation for reducing emissions (e.g., Creutzig et al., 2016, 2018, 2023), most IAMs still do not adequately represent the human system

components necessary for assessing climate-relevant behaviours – whether these behaviours are direct responses to climate change or arise from other broader drivers (Beckage et al., 2020; van Valkengoed et al., 2025).”

## 2 Existing models review

- Line 70: **affects** not affect
  - Corrected
- The order of paragraphs 4 and 5 could be swapped. This way, the section would first review existing models and then conclude by describing how these models differ from the presently introduced model. This would improve flow
  - Thank you for the suggestion. We have swapped the paragraphs with minor edits to the language to improve the flow.

## 3 Model description

- Overall, a very clear and comprehensive model description with good justifications of modelling choices and mechanistic thinking
- This section is missing a paragraph providing an overview of FRIDA (ie. it is a global model, GDP is endogenous, what exogenous inputs are included, etc). The aggregation level is mentioned a few times, so it should be explicitly described
  - Thank you for pointing this out. We will start the Model Description section with a brief overview of FRIDA v2.1 and reiterate that the model described in this paper is embedded within this larger model:  
“Given that our model is embedded within the novel global IAM, FRIDA v2.1, we first present a brief overview of the FRIDA model (see Schoenberg et al., 2025 for more details). FRIDA represents the climate and human systems together, each represented with similar levels of fidelity. FRIDA places strong emphasis on feedback dynamics and interpretability. It endogenously incorporates key components of the Earth system such as the radiation balance, carbon and water cycles, and it does so alongside the endogenous representation of human factors like population, economy (including GDP), agriculture, and energy use. The only exogenous inputs to FRIDA are solar radiation cycles, Montreal gas emissions, and global policy (economic, climate or otherwise). The FRIDA model is capable of simulating from 1980-2150, reproducing historical behaviour with no additional exogenous inputs.”

- For all equations, I like to see variables defined in a caption even if they are defined in the text, so that equations can be read as separate from the text (like with figure captions). Saves readers from doubling back and searching the text for variable abbreviations
  - We have updated this section to ensure that variables are defined in the line below each equation along with units.
- Line 167: does FRIDA allow stocks of food commodities to be carried over between years or does the market clear?
  - FRIDA does not explicitly model inventory stocks for food commodities and assumes that inventory dynamics are not a key driver of global food demand. For crops, global production is determined by multiplying capacity (crop land) by average yield. For animal products the production rate depends upon capacity (grazing land), grazing yield, feed production, animal product growth efficiency (the conversion factor between raw calories from either feed or the land, and animal product calories) as well as the aquatic animal product share to account for the land not needed for “seafood grazing”. The demand/supply balance for any given year influences supply-side decision-making for changing future production capacity, feed demand for animal products, and/or yield. However, on the supply side a buffer is included to account for desired reserve capacity to buffer fluctuations in demand.
  - For improved transparency we have edited the text as such:  
 “After accounting for population and unit conversion, total demand influences total production ( $\text{Pcal}\cdot\text{yr}^{-1}$ ) in the LUA module. Here, the supply-demand balance each year influences future decisions for adjusting production capacity and yield. Additionally, a reserve capacity multiplier is included to buffer against demand fluctuations, implicitly capturing the role of strategic reserves without modelling explicit inventory dynamics. Global food inventory dynamics were deemed unimportant over the multi-decadal time scale of FRIDA.”
- Figure 175: The clear visualisation of feedback loops is a nice addition to this schematic diagram. However, the colour codes and labels on the loops are redundant and the schematic is a bit hard to read. Placing some more of the important values inside shapes (like DADD is now) could help with readability – particularly the values in bold now, for example
  - The diagram follows the conventions of causal loop diagrams used in system dynamics. The shape around DADD represents a stock, which is

used to emphasize that the variable accumulates past behaviour and adjusts gradually.

- Nevertheless, we have added additional colour-coded shapes to the diagram as suggested. We have also shortened the loop labels. We hope that these changes serve to improve its readability.
- Line 375: Are only globally relevant extreme events included? What qualifies an event as event globally relevant, if so?
  - Extreme events here are defined by a set of indices calculated at the grid-cell level of Earth System Model data, with the local exposures aggregated up to the global level and then expressed as a function of STA. In this way, we aren't assessing the global relevance of each event, but representing the accumulated global total of individual grid-cell level occurrences normalized by population. For more details on the representation of extreme events, please refer to Wells et al. (2025) cited in the paper.
  - For clarity we have refined the sentence as such:  
“Expressed as a function of global mean surface temperature anomaly (STA), the climate indices aggregate local record-breaking exposures calculated at the grid-cell level data from 35 climate models across seven metrics as found in Li et al. (2023): annual total precipitation, maximum 1-day precipitation, days with heavy precipitation, warm days, heatwave, sequential precipitation-humid heatwave, and compound drought and heatwave.”

#### **4 Model Calibration**

- Line 463: If the FAO data was used, shouldn't the EAT Lancet target diet be scaled up to include calories wasted at the household and retail levels?
  - Indeed, FAO data includes consumer waste since data on actual household consumption is limited. We did not scale up the EAT Lancet target used as the “healthy reference” since a waste multiplier would lock-in food waste as part of a healthy diet. This is counter to the function of the overconsumption risk loop, which is meant to motivate individuals to reduce their demand, whether the amount of actual food consumed or food wasted.
  - However, we acknowledge that this is a limitation since the concept of food waste is not explicitly modelled in FRIDA. We have revised the limitation section to make this transparent:  
“FRIDA does not explicitly model the concept of food waste as a separate process. As a result, waste is included in both food production and

demand figures. This simplification reflects the current lack of consistent time-series data on actual household demand and consumption, which limits the ability to calibrate the model to waste-adjusted consumption levels. Consequently, there is a discrepancy between the consumption rate (which includes waste) and target healthy reference level (which excludes waste). This reference level is not scaled with a waste multiplier to avoid embedding waste as a normative component of a healthy diet. This modelling choice ensures that the benchmark remains waste-free and motivates the reduction of demand, whether through lower actual consumption or reduced waste. Future work could address this limitation by explicitly modelling food waste as a distinct, endogenously evolving quantity. That is, the behavioural feedback processes would influence both actual consumption and food waste separately, enabling a more nuanced representation of dietary behaviours.”

- Line 512: Is there a reference for all FRIDA parameters included in uncertainty analysis?
  - We will upload a data file with all the parameters varied in FRIDA along with the ranges in the external FRIDA’s data repository, and include a reference in the text.

## 5 Simulation results

- Figures in this section are nice and clear
- It would be interesting to discuss more about the weighting factors, ie. How much did climate vs health risks influence diets in the model?
  - We have introduced a new paragraph in this section that responds to this comment:

“At this juncture, it is important to reiterate that PCCR, PCR and PSV are not independent factors; rather they interact multiplicatively to shape personal norms and, by extension, dietary intentions. While the feedback effects are interdependent, the calibrated weights offer insight into the relative influence of each feedback process. For total food demand, the median sensitivity to PSV is estimated at 0.936, while sensitivities to PCR and PCCR are –0.798 and –0.138, respectively. In the case of animal products demand, the corresponding median estimates are 0.974 for PSV, –0.724 for PCR, and –0.407 for PCCR. These figures highlight the dominant role of perceived social value in shaping demand, while also illustrating the moderating effects of perceived consumption risk and climate change risk. On average, individuals are least responsive to PCCR, with this effect



being more pronounced for total food demand than for animal products demand. This pattern reflects real-world dynamics, as climate change is more strongly associated with meat consumption; that is, people are likely to reduce their animal products demand more than their overall caloric intake.”

- Line 597: The discussion should include some review of how this rebound could possibly be avoided based on behavioural literature
  - We did not discuss policy conclusions for avoiding or mitigating the rebound since GMD explicitly states that such discussions are beyond the scope of the journal. Also, as mentioned, we are preparing a separate manuscript, where we run policy experiments. Therefore, we believe that this discussion should be reserved for that manuscript instead.
- Line 601: typo
  - Corrected
- Line 619: production dynamics **have**
  - Corrected

## 6 Conclusions

- Line 639: we close **one** human – climate feedback. Other behavioural feedbacks remain GDP-dependent in the current model
  - Corrected
- Line 640: addressing **a** current gap (there are certainly other gaps)
  - Corrected
- Line 689: How applicable would this the EBM be to national or regional food demand? Would it be possible to calibrate it for the level of aggregation used in other common IAMS?
  - We believe that this model would be applicable to models with different levels of aggregation. Thank you for these questions, which has inspired the addition of a new paragraph in this section:  
“Future research could also explore the applicability of our framework to other models beyond FRIDA. For models operating at the national or regional spatial resolutions, the structures presented in our endogenous behavioural model could be easily adapted and calibrated using appropriate time-series data. In such cases, particular attention should be given to the demand-supply dynamics that shape consumer behaviour.



Specifically, localized supply needs to encompass both domestic production and imports. For models that disaggregate food products (e.g., by crop and animal type), more extensive adaptation would be required. Beyond arraying the structures for each food category, additional components must be introduced to capture the matrix of within- and across-type relative scarcity/accessibility and diet substitution (e.g., beef to poultry vs. beef to soy). Despite such structural modifications, we anticipate that the core behavioural feedback processes described in this paper would remain applicable, offering a foundation for modelling dietary behaviours across diverse food system contexts.”

- Line 707: remove "lastly", as it could imply this paragraph focuses on another limitation of the model rather than an avenue for future work
  - Removed as suggested
- Line 709: various energy demands ... **are** modelled
  - Corrected
- Add one sentence to the very end reiterating the points in the first paragraph of the conclusion, to leave the reader with a strong takeaway
  - We have added the following sentence at the very end:  
“Ultimately, by endogenizing behavioural feedbacks within a dynamic modelling framework, we provide a pathway for more robust and responsive representations of behavioural change and human-climate interactions, addressing a critical gap in IAMs and advancing the potential for demand-side assessments.”

## Response to Referee #2

### General Comments:

The model presented in this manuscript represents a significant contribution to efforts to integrate human and climate processes by demonstrating the importance of endogenous feedback in shaping dietary choices. Simulation results demonstrate that including endogenous human behavior generates distinct projections for future food demand relative to projections that rely on GDP alone. These results make a compelling case to account for endogenous behavior through factors like perceived food accessibility and behavioral norms in addition to income when modeling food demand.

Thank you for the positive comments as well as the detailed list of technical corrections to be made. We have documented the changes we have made following your comments below.

### **Specific Comments:**

It is helpful that Figure 2 includes variable acronyms/shorthand (e.g., DADD) in parentheses along with the complete names. I recommend including more of these terms for ease of reference (e.g., STA, PSV, PCR, PCCR).

We have include more acronymns in the figure as suggested.

I found the logic unclear for why consumption declines after a certain level of income. Why is it that higher socioeconomic class consumers are less influenced by the symbolic status of food consumption (line 243)?

We have revised the text to provide a more clearer explanation, which clarifies the logic: "A social-psychological perspective might provide a better explanation: less accessible dietary behaviours can amass a symbolic value as markers of socioeconomic status, making them more desirable to individuals from lower socioeconomic groups as a form of compensatory consumption aimed at signalling upward social mobility or aspirational identity (Chan and Zlatevska, 2019; Doyle and Richardson, 2025). Higher socioeconomic class consumers, having greater material security and social capital, are generally less influenced by the symbolic status of consumption; instead, they are more likely to prioritize post-material concerns and cultural values such as health, environmental sustainability, and ethical considerations (Doyle and Richardson, 2025; Vranken et al., 2014)."

I think equation 10 would be more clearly written if it began with  $\omega_{dn}(t) = \omega_{pn}(t)$

Agreed! We have corrected the equation.

I count 6 climate indices, not 7, in section 3.2.1 lines 378-80. Please clarify.

We indeed missed including "warm days" which has now been added to the list.

In section 3.2.1 line 404, the reference to the "SLR Impacts and Adaptation module in FRIDA" could be confusing since it is not illustrated as a module in Figure 1. I suggest clarifying that it is part of the Climate module in FRIDA by using the term "sub-module" or "formulation", such as: "The SLR Impacts and Adaptation sub-module of the Climate module in FRIDA"

The SLR sub-module, which estimates the sea level rise, is indeed in the Climate module. However, the SLR Impacts and Adaptation sub-module is separated and nested within the Economy module since it primarily deals with economic damages and economic effects.

We have revised the text as such for clarity: “The SLR sub-module in the Climate module computes changes in sea level from climatic processes, whereas the SLR Impacts and Adaptation sub-module in the Economy module estimates the number of people exposed to SLR-induced floods from coastal populations, measured in  $\text{Mp}^{-1}\cdot\text{yr}^{-1}$  (see Ramme et al., 2025).”

In section 4 line 452-3, the phrase “uncertainty is inherent in the model” could be confusing since the model itself is deterministic, not stochastic. I suggest rephrasing to say “in the model’s parameterization” instead.

Thank you for pointing out this ambiguity. We have rephrased the sentence as suggested.

I suggest revising the section 5 header to “Simulation results and discussion” (line 519) to better reflect the contents of that section.

We have accepted this suggestion and corrected the manuscript accordingly.

Were any runs analyzed individually? (see line 604-5)

Although we do not show individual runs in the results, we did analyze the observable behaviour modes within the uncertainty ensemble. In particular, we analyzed runs to understand why there was a reversal in behaviour change for runs within the upper limit of the 95% CI. We also analyzed why perceived accessibility decreased towards the end of the simulation in the lower bound of the 95% (due to climate-induced inflation affecting GDP).

However, since we do not report the runs individually, we have now replaced “among some sample runs” with “within the uncertainty range” to avoid any potential confusion.

In section 5 line 630, suggest clarifying by adding “between the EMB and GDP-driven simulations” to the end of this sentence.

We have added it to the end of the sentence.

## Technical Corrections:

Include consistent use of significant figures in Appendix A. Rounding to the nearest integer fails to show the range of uncertainty for several of the time constants for which the value, min, and max are all set to 1.

Our rationale for rounding to the nearest integer for time constants was to avoid providing a false sense of precision. Since these were all estimated from calibration, and the model is not sensitive to small changes in time constants, we did not want to imply overconfidence in the model's predictive power. However, these changes can be easily made in the revision if higher level of precision is meaningful for interpreting the uncertainty in the calibration.

Line 114: should be "lifestyle" not "lifestyles"

Corrected

Line 151: suggest "Additional indirect feedback" instead of "Additionally, more indirect"

Corrected

Line 156: Figure 1 legend should say "Sub-system" not "Subs-system"

Corrected

The rightmost reinforcing loop in Figure 2 should say "personal norm" not "person norm"

Removed after comment from Referee #1 to improve readability.

Line 176: Figure 2 legend should include "labels" after "blue" and "purple"

Caption has been re-phrased.

Line 202: should be "such as price" not "such price"

Corrected

Line 203: should be "price" not "prices" in the first instance

Corrected

Line 213: suggest rephrase, changing “that” to “and is set to” so that it is clear that the sensitivity term is less than one, not relative scarcity: “ $\beta_s$  is the sensitivity of demand to relative scarcity and is set to less than 1”

Corrected

Line 218: suggest adding “the” to read “the animal products balance”

Corrected

Line 224: suggest including beta in parentheses, as ( $\beta_i < 1$ ), to make it clear that the constraint is not applied directly to changes in income.

Corrected

Line 232: add “demand” after “animal products”, to read “animal products demand”

Corrected

Line 251: suggest “decreases at a decreasing rate” rather than “decreases decreasingly”

Corrected

Line 308: should be “require” not “requires”

Corrected

Line 334: should be “norms” not “norm”

Corrected

Line 338: should be “emphasized” not “emphasize”

Corrected

Line 351: the citation (Mathematical builtins, 2025) missing from the reference list

The citation is listed in Line 830, organised by author name (isee systems) which was suppressed following this citation style. We have now shifted it down along with other citations that start with M

Line 374: suggest “(listed below)” instead of “(see below for list)” since the indices are named in text just two sentences later; the reference to a list could imply a different format.

Corrected

Line 375: specify "It" - if it is the Climate module, then start the sentence "The Climate module estimates"; or if "it" is the climate indices, then start the sentence "The climate indices estimate"

Corrected to the latter

Line 377: should be "reproduce" not "reproduces"

Corrected

Line 388: should be "diminish" not "diminishes"

Corrected

Line 408: should be "perceptions of risk or abnormality are sensed" not "is sensed"

Corrected

Line 430: should be "times" not "time" in first instance, as in "smoothed three times"

Corrected

Line 527: suggest "demands" not "demand", as in "various average daily food demands"

Corrected

Line 570: should be "catch" not "catches"

Corrected

Line 591: should be "reinforce" not "reinforces"

Corrected

Line 601: typo in "Therefore"

Corrected

Line 704: should be "demands" not "demand" and "are" not "is", as in "the various energy demands in the present version are modelled primarily as functions"

Corrected