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The DSK stock-flow consistent agent-based integrated assessment model

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ABSTRACT

We present an updated, stock-flow consistent version of the 'Dystopian Schumpeter meeting Keynes' agent-based integrated assessment model. By embedding the model in a fully specified accounting system, all balance sheet items and financial flows can be explicitly and consistently tracked throughout a simulation. This allows for improved analysis of climate change and climate policy scenarios in terms of their systemic implications for agent and sector-level balance sheet dynamics and financial stability. We provide an extensive description of the updated model, representing the most detailed outline of a model from the well-established 'Keynes + Schumpeter' family available to date. Following a discussion of calibration and validation, we present a range of example scenarios.

1. Introduction

This paper provides a full description of the updated, explicitly stock-flow consistent (SFC) version of the *Dystopian Schumpeter meeting Keynes* (DSK) agent-based integrated assessment model (Lamperti et al., 2018, 2019a, 2020, 2021) representing the first integrated assessment model featuring full stock-flow consistency, agent heterogeneity, bottom-up climate impacts and endogenous GDP growth as well as cyclical fluctuations. Over the past 15 years, the use of agent-based models (ABMs) in macroeconomic analysis has increased in popularity, proposing a wide array of frameworks for the analysis of business cycle fluctuations, long-term growth, financial crises and their interplay (see e.g. Fagiolo and Roventini, 2017, Dawid and Delli Gatti, 2018 and Dosi and Roventini, 2019 for an overview). Somewhat more recently, complexity approaches in general and AB modelling in particular have also seen applications within the literature on environmental/ecological economics (Balint et al., 2017), with several macroeconomic frameworks which incorporate environment-energy-economy interactions being proposed (see Naumann-Woleske, 2023, for a recent review). The DSK model, originally proposed by Lamperti et al. (2018), is the first agent-based integrated assessment model (IAM), providing an alternative and complementary perspective to the analyses produced by more conventional IAM frameworks (e.g. Bosetti et al., 2006; Leimbach et al., 2010), both for what concerns impact assessment (Lamperti et al., 2019a, 2021) and climate policy (Lamperti et al., 2021).

Several features can make an agent-based approach a valuable complement or alternative to more conventional approaches to integrated assessment modelling (see also Farmer et al., 2015; Lamperti et al., 2019b). Most obviously, ABMs are inherently well-suited for the incorporation of agent heterogeneity along multiple dimensions and their interactions. Suitably specified ABMs can hence be used to investigate issues such as changes in the distribution of income or the sectoral composition of economies as a consequence of climate change and climate policy, as well as interactions occurring on goods and financial markets. Moreover, ABMs allow for a more detailed depiction of institutional settings and policy measures than is typically the case in general equilibrium frameworks. ABMs also do not make use of the usual assumptions on agent rationality and perfect foresight or rational expectations typically underlying general equilibrium models, instead positing that model agents follow a set of more or less sophisticated heuristics in their decision-making, which may adapt and evolve over time. This use of alternative behavioural assumptions can provide an important comparative perspective to the optimisation-based results

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obtained from standard IAMs. Savin et al. (2022) argue for the integration of a range of disciplines such as behavioural and political sciences, psychology and sociology to improve the modelling of climate polices and how their effects may depend on bounded rationality, interactions and peer effects, or voting and political lobbying (cf. Di Benedetto et al., 2024; Lackner et al., 2024). They advocate the use of ABMs for this purpose since they allow for a rich modelling of behavioural rules at the level of individual entities. Virtually all existing macroeconomic ABMs feature short-run endogenous business-cycle dynamics, including periods of deep crisis. This means that an agent-based IAM can be used to study not only the long-run implications of climate change and climate policy but also their short-run impacts which are typically of great interest to policy-makers. Finally, ABMs have traditionally strongly emphasised the modelling of the financial sector and real-financial interactions. By contrast, this dimension is underdeveloped in conventional IAMs (Sanders et al., 2022), meaning that an AB approach can provide useful and unique insights on issues such as the financial stability implications of climate change and climate policy.

This paper represents a methodological advancement in particular regarding the latter dimension. It embeds the DSK model in a fully consistent accounting framework, following the paradigm of stock-flow consistent modelling (Godley and Lavoie, 2007). This has become an important component of AB macroeconomics (Caiani et al., 2016), and models using an SFC approach have recently also begun to feature prominently in the literature on ecological macroeconomics (e.g. Dafermos et al., 2017; Monasterolo and Raberto, 2018; Jackson and Victor, 2020; Carnevali et al., 2024). The use of an SFC framework makes it possible to explicitly and consistently track all balance sheet items and financial flows in the model, allowing for a detailed analysis of the systemic implications of particular scenarios and trajectories in terms of changes in financial ratios and balance sheet positions at the agent and/or sector level. In addition, the presence of an SFC structure excludes the possibility of biases in simulation results arising from accounting errors, and increases the reliability of the initialisation and calibration process. Finally, it is also an important building block for planned future extensions of the DSK model which we discuss in the conclusions.

The main purpose of the paper is to provide an exhaustive outline of the updated framework, representing the most detailed description of a model of the ‘Keynes + Schumpeter’ (K+S)/DSK family available to date. Since this is one of the most widely applied macroeconomic ABM frameworks in the literature, we make an important contribution to improving the transparency and reproducibility of macroeconomic agent-based modelling (cf. Dawid et al., 2016). Additionally, a major focus of the work presented here has been to improve the usability and accessibility of the model code, with a view to enabling interested users to apply and extend the model in their own work. Finally, we also present some simple example simulations, the purpose of which is to illustrate the baseline dynamics of the framework and thereby supplement the model description. In line with findings from previous versions of the DSK model (Lamperti and Roventini, 2022) as well as other non-standard frameworks, we find that aggressive carbon taxation may imply a significant macroeconomic cost (especially if not supplemented by redistributive policies; cf. Fierro et al., 2024). We also show that the macroeconomic effects of climate impacts depend strongly on the channel through which climate change affects the economy (cf. Bazzana et al., 2024), with shocks to labour productivity slowing down the growth rate of the economy and shocks to capital stocks giving rise to heightened volatility and financial instability. Finally, we confirm that, in line with previous findings from K+S models (e.g. Dosi et al., 2010) and demand-driven macroeconomic models more generally, fiscal policy interventions (here in the form of increased unemployment benefits) can contribute to macroeconomic stabilisation.

The paper proceeds as follows: Section 3 presents a broad overview of the model’s main features and its accounting structure. Section 4 contains a brief model description, with a fully exhaustive one being provided in Appendix A. Section 5 describes the main accessibility and usability upgrades which were made to the model code. Section 6 describes the calibration and validation of the model, with additional details being given in Appendix A. Section 7 presents some example simulation experiments. Section 8 concludes. Appendix B contains tables giving a full list of all model parameters and initial values, along with the respective values used in the simulations shown in the paper.

2. DSK - a comparative perspective

Providing a complete survey of SFC models or ABMs with environmental, ecological or energy-related features (E-SFCs and E-ABMs) is beyond the scope of this paper. Here we instead aim to highlight the distinguishing features of DSK as well as areas in which the model can still be improved by comparing it to a selected list of other models, including four E-SFCs (DEFINE, EIRIN, GEMMES, TEMPLE, and Carnevali et al., 2024) and two E-ABMs (MATRIX and the expanded version of the Eurace model presented by Ponta et al., 2018). Though not exhaustive, we believe that this selection is instrumental to our comparative perspective, as the chosen models collectively capture a broad spectrum of modelling features found in the literature.[1] We select and categorise some of the most relevant modelling features into three main groups, as summarised in Table 1: (i) modelling framework; (ii) core ecological components; and (iii) core macroeconomic components. For the modelling framework, we simply indicate whether the models considered are SFC, ABM, or both. We then identify two key ecological components, that is whether the models depict material flows and whether they incorporate climate-economy feedback. Finally, we observe that macroeconomic features show the greatest variation across models, warranting a more detailed discussion before proceeding with the comparison.

A first distinction can be drawn between models with endogenous or exogenous/absent technological change. Typically, the former approach represents transition dynamics as a choice between green and brown capital. In contrast, accounting for endogenous technological change introduces an additional dimension, where existing technologies undergo continuous improvements. This introduces a broader range of technological options, characterised by varying degrees of “green” and “brown”, and makes the batch of available technologies endogenous to policy and the institutional setting. Another relevant aspect is the models’ ability to capture inflation dynamics resulting from transition pathways and climate shocks, particularly cost-push, demand-pull, and Phillips-curve mechanisms. This is particularly needed for analysing short-run macroeconomic adjustments, along with three other key elements found in the literature: (i) modelling energy as a consumption good, in addition to its role as a production input; (ii) incorporating explicit behavioural responses to climate shocks, such as precautionary saving or reduced investment in light of increasing climate risks; and (iii) the chosen functional form for the production function, specifically whether input substitution is permitted and under which conditions. Lastly, we consider distributional aspects, which, based on our reading of the literature, focus on the presence of heterogeneous skills and wages, as well as the feedback loop from income distribution to aggregate demand, often represented through heterogeneous propensities to consume out of income.

An inspection of Table 1 suggests two main takeaways: firstly, all E-ABMs are also SFC, while all E-SFCs lack the detailed microeconomic

[1] Another macroeconomic model rooted in out-of-equilibrium dynamics and post-Keynesian economic theory that can be used for the analysis of economy-environment-energy interactions is E3ME-FTT (Mercure et al., 2018). We left this model out of the present comparison as the focus on sectoral heterogeneity and multi-country dynamics make it different from the other models briefly surveyed here.

Table 1
Main features of some agent-based and/or stock-flow consistent models with environmental/ecological/energy components.
MF=Material Flow; CF=Climate Feedback; ETC=Endogenous Technological Change; DF=Distributional Feedback; INFL=Inflation; HSW=Heterogeneous Skill Wage; EC=Household Energy Consumption; EBR=Explicit Behavioural Response (to climate shocks); FC= Fixed-Coefficients (production function).

Model	References	Framework		Ecology		Economy						
		SFC	ABM	MF	CF	ETC	DF	INFL	HSW	EC	EBR	FC
DEFINE	Dafermos et al. (2017, 2018)	✓	✗	✓	✓	✓	✗	✗	✗	✗	✓	✓
EIRIN	Monasterolo and Raberto (2018, 2019)	✓	✗	✗	✗	✗	✗	✓	✓	✓	✗	✓
GEMMES	Bovari et al. (2018, 2020)	✓	✗	✗	✓	✗	✗	✓	✗	✗	✗	✓
TEMPLE	Jacques et al. (2023)	✓	✗	✗	✗	✗	✓	✓	✗	✓	✗	✓
(no name)	Carnevali et al. (2024)	✓	✗	✓	✓	✓	✓	✓	✗	✗	✓	✓
Eurace	Ponta et al. (2018)	✓	✓	✗	✗	✗	✗	✓	✗	✗	✗	✓
MATRIX	Ciola et al. (2023), Bazzana et al. (2024)	✓	✓	✗	✓	✗	✗	✓	✗	✗	✗	✗
DSK-SFC	This paper	✓	✓	✗	✓	✓	✓	✓	✗	✗	✗	✓

structure typical of the ABM paradigm. Secondly, DSK is one among few models featuring endogenous technological change, and the only one depicting technological change as an R&D-driven process at a disaggregated level.[2] It inherits the Schumpeterian engine from its K+S predecessor (Dosi et al., 2010), which was expanded to incorporate endogenous innovations to energy efficiency and emission intensity already in the original DSK (Lamperti et al., 2018). We also observe that all models, except MATRIX,[3] utilise a fixed-coefficients production function. One key implication of this is that energy price shocks (oil shocks, carbon pricing, etc.) tend to have a large macroeconomic impact, as the system is unable to quickly substitute inputs. However, some degree of dynamic flexibility can be achieved through technological change and physical capital adjustment (e.g., brown vs green, or energy-intensive vs. energy-efficient capital). DSK combines a rigid energy demand for production purposes in the short run with a more flexible one in the long run. Indeed, the substitution of energy with other inputs occurs, but it takes time, as it can only be achieved through investment in more energy-efficient capital and technological innovation. This distinction between the short and long run offers a realistic description of macroeconomic adjustments in response to energy shocks, accounting for both the timing of these adjustments and the costs associated with investments in innovation and physical capital.

There are also several key characteristics of the stock flow consistent version of DSK which are shared with existing models, such as inflationary dynamics (all, except DEFINE), distributional feedback (TEMPLE, Carnevali et al., 2024), and climate feedback (DEFINE, MATRIX, Carnevali et al., 2024). We would argue, however, that DSK-SFC unifies them in a comprehensive framework that allows for a more detailed analysis of both short-run and long-run dynamics. This integration is particularly important for studying the economic impact of climate policies, as it brings together elements of macroeconomic stability, technological progress, and environmental sustainability. Lastly, it is important to acknowledge that our model currently lacks some features found in ecological SFC models. These include the full integration of material flows (DEFINE, Carnevali et al., 2024), wage and skills heterogeneity (EIRIN), direct household energy consumption (EIRIN, TEMPLE), and explicit behavioural responses to climate shocks (DEFINE, Carnevali et al., 2024). This indicates that while this paper takes a step forward by incorporating an SFC structure into the DSK model, some research questions will need further model developments.

[2] DEFINE and Carnevali et al. (2024) embed a Kaldor–Verdoon mechanism whereby productivity growth is a function of real output growth. However, this mechanism works at the aggregate level and does not affect technological parameters such as energy efficiency and emission intensities.

[3] Ponta et al. (2018) adopt a mixed production function, in which capital and labour are substitutes, but energy must be employed in fixed proportion to output.

3. Overall structure

With the exception of a newly added separate fossil fuel sector, the sectoral structure of the model is identical to that of previous versions of the DSK model (Lamperti et al., 2018, 2019a, 2020, 2021), with the difference that all balance sheet items and transaction flows are explicitly modelled and tracked during simulations.

The DSK framework is part of the *Schumpeter meeting Keynes* (K+S) family of models (Dosi et al., 2010, 2013, 2015, 2017b). As such, the economic core of the model is formed by an agent-based firm sector, differentiated into consumption good firms and capital good firms (C-Firms and K-Firms hereafter). K-Firms produce capital goods which possess heterogeneous characteristics in terms of labour productivity, energy efficiency and emission intensity. To produce them, K-Firms use production techniques which are also heterogeneous in terms of labour productivity, energy efficiency and emission intensity. New and superior vintages of capital goods as well as novel techniques emerge as the outcome of an innovation process driven by K-Firms' endogenous R&D expenditure. This ultimately drives long-term growth in the model. K-Firms sell capital goods to C-Firms, which use them (alongside labour and energy) to produce a homogeneous consumption good. The investment of C-Firms depends on their expected demand and on the process of technological change. This can trigger Keynesian endogenous business cycles. Firms' activities are financed through retained earnings and, in the case of C-Firms, loans from a banking sector. Households consume and receive income in the form of wages for supplied labour, interest on deposits, dividends from firms, banks and the energy sector, as well as unemployment benefits. The government collects taxes and spends on unemployment benefits as well as, possibly, the bailout of failing banks. The central bank acts as a buyer of last resort for government bonds and creates reserves which it supplies to the banking sector through advances. The DSK model also includes an energy sector which supplies the firm sector with energy needed for production and which also engages in endogenous R&D. Moreover, it features a climate module which receives emissions from the economic model and can feed back on the latter through climate shocks. Finally, the version of the model presented here also includes a separate fossil fuel sector which sells fossil fuels as an input to the energy sector.

Fig. 1 provides an overview of the model, including market and non-market interactions between sectors and the role of the climate module. Table 2 gives more detail on the accounting structure, showing the balance sheet matrix including the assets and liabilities held by each sector. The consumption and capital goods sectors, as well as the banking sector, consist of multiple and heterogeneous agents, while the other sectors (including energy and households) can be considered as aggregate entities. Table 3 shows the transactions flow matrix of the model, summarising the transactions between sectors and showing how these are financed.

The balance sheet and transaction flow matrices can be used to derive the accounting identities that must be satisfied for the model to be formally stock-flow consistent. To ensure stock-flow consistency

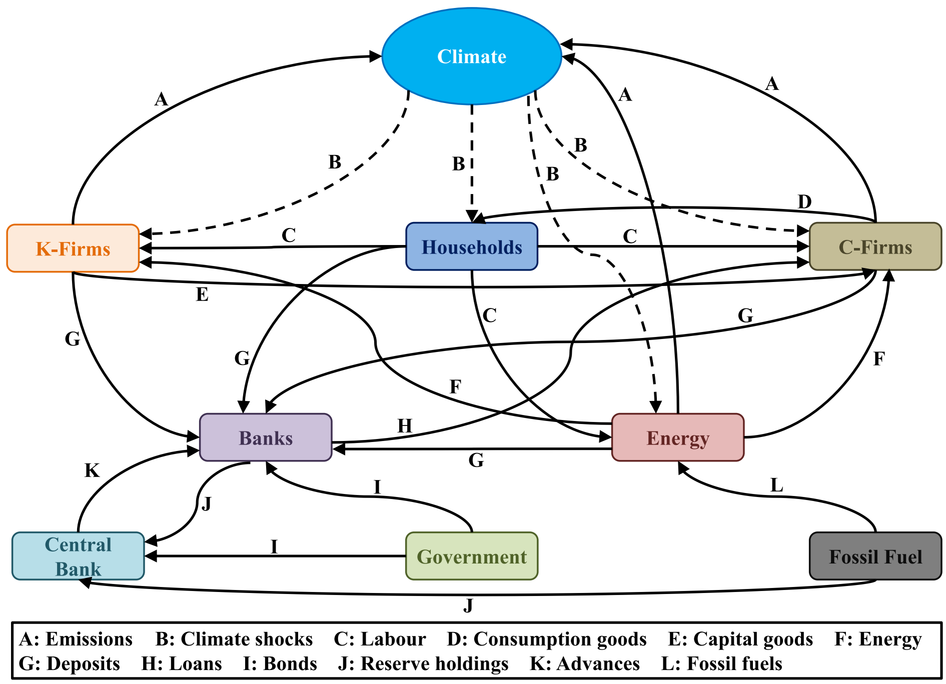

Fig. 1. Overview of the DSK stock-flow consistent model. Arrows represent market or non-market interactions between sectors/model components as detailed in the legend.

Table 2
Balance sheet matrix.

	Households	C-Firms	K-Firms	Banks	Gov.	CB	Energy	Fossil	Σ
Bank Deposits	$+D_h$	$+D_c$	$+D_k$	$-D$			$+D_e$		0
Gov. Bonds				$+GB_b$	$-GB$	$+GB_{cb}$			0
Loans		$-L$		$+L$					0
CB Reserves				$+R_b$		$-R$		$+R_f$	0
CB Advances				$-A$		$+A$			0
Fixed Capital		$+K$					$+K_e$		$K+K_e$
Inventories		$+Inv$							Inv
Σ	NW_h	NW_c	NW_k	NW_b	NW_g	NW_{cb}	NW_e	NW_f	$K+K_e+Inv$

Table 3
Transactions flow matrix.

	Households	C-Firms	K-Firms	Banks	Government	Central Bank	Energy	Fossil	Σ
Consumption	$-C$	$+C$							0
Investment		$-I$	$+I$						0
Benefits	$+UB$				$-UB$				0
Taxes	$-Tax_h$	$-Tax_c$	$-Tax_k$	$-Tax_b$	$+Tax$		$-Tax_e$		0
Wages	$+W$	$-W_c$	$-W_k$				$-W_e$		0
Fuel							$-FF$	$+FF$	0
Energy		$-E_c$	$-E_k$				$+E$		0
Dividends	$+Div$	$-Div_c$	$-Div_k$	$-Div_b$			$-Div_e$	$-Div_f$	0
Interest Loans		$-iL$		$+iL$					0
Interest Deposits	$+iD_h$	$+iD_c$	$+iD_k$	$-iD$			$+iD_e$		0
Int. Gov. Bonds				$+iGB_b$	$-iGB$	$+iGB_{cb}$			0
Int. Reserves				$+iR$		$-iR$			0
Int. Advances				$-iA$		$+iA$			0
Transfer CB					$+T_{cb}$	$-T_{cb}$			0
Transfer Entry	$-T_h$	$+T_c$	$+T_k$	$-T_b$	$-T_g$				0
Bailout				$+Bail$	$-Bail$				0
Saving	(Sav_h)	(Sav_c)	(Sav_k)	(Sav_b)	(Sav_g)	(Sav_{cb})	(Sav_e)	(Sav_f)	0
Δ Deposits	$-\Delta D_h$	$-\Delta D_c$	$-\Delta D_k$	$+\Delta D$			$-\Delta D_e$		0
Δ Gov. Bonds				$-\Delta GB_b$	$+\Delta GB$	$-\Delta GB_{cb}$			0
Δ Loans		$+(\Delta L)$		$-(\Delta L)$					0
Δ Reserves				$-\Delta R_b$		$+\Delta R$		$-\Delta R_f$	0
Δ Advances				$+\Delta A$		$-\Delta A$			0
Σ	0	0	0	0	0	0	0	0	

during simulations of the model, all transaction flows and balance sheet items are explicitly tracked. At the end of each simulation period, the model performs a series of checks at the agent, sectoral and aggregate levels to ensure that no accounting identities have been violated during the period. Stock-flow consistency enhances the model's ability to generate reliable economic dynamics. By accurately tracking the balance sheet positions of agents, exit/bankruptcy conditions for firms and banks are correctly depicted and firm entry is modelled without an exogenous injection of wealth, avoiding potential bias in results arising therefrom. Consistent tracking of balance sheet items also allows for the integration of stocks into key behavioural equations, such as the consumption function. Furthermore, the SFC framework enables the precise monitoring of stock-flow ratios, improving the modeller's ability to identify statistical steady states.

In making the model stock-flow consistent, assumptions regarding agent behaviour were left unchanged as far as possible, with the focus being on the modelling of balance sheet items and flows which were previously not or not fully tracked. One major exception is the firm entry process. To enable households to finance the entry of new firms, the consumption function was changed to allow households to save, whereas in previous versions of DSK and K+S, households were always pure hand-to-mouth consumers. In addition, as outlined in the model description, a secondary market for capital goods was introduced to enable entering firms to purchase an initial stock of capital. Table 4 summarises the main changes which were made to achieve full stock-flow consistency.

4. The model

The present section provides a compact overview of the model, describing agent types and their behavioural rules. A fully exhaustive model description, including the sequence of events taking place within each simulation period, is provided in Appendix A.

4.1. Households

The household sector is modelled as an aggregate entity which earns wages (in exchange for supplying labour), unemployment benefits, as well as dividends from firms, banks and the energy sector. The maximum aggregate labour supply of households (representing the labour force) changes at an exogenous rate reflecting population growth (or decline); up to this maximum, households will supply any amount of labour demanded at the current nominal wage rate. For any part of the aggregate labour supply which is not employed, households receive an unemployment benefit payment.

Households' nominal consumption demand is given by

$$C_{d,t} = \alpha_1 \left(W_t + UB_t - Tax_t^H \right) + \alpha_2 \left(Div_{t-1} + iD_{h,t} \right) + \alpha_3 D_{h,t-1} \tag{1}$$

where $\left(W_t + UB_t - Tax_t^H \right)$ is wage and benefit income net of taxes, $\left(Div_{t-1} + iD_{h,t} \right)$ is income from dividends and interest on households' bank deposits, and $D_{h,t-1}$ is the stock of deposits held by households. Households hence have different propensities to consume out of wage and benefit income, dividend and interest income, and wealth. This functional form is very similar to what is found in many other macroeconomic ABMs (Dawid and Delli Gatti, 2018), as well as in aggregate SFC models (Nikiforos and Zezza, 2017). All household savings are held in the form of bank deposits and households cannot borrow to finance consumption.

The nominal wage rate follows a Phillips curve-type rule (see equation (A.3) in the detailed model description), being a decreasing function of the unemployment rate and increasing in current inflation. In addition, the nominal wage is pegged to long-run labour productivity growth.

4.2. Capital good firms

The sector of capital goods firms (K-Firms) consists of $N1$ individual firms. Each firm produces a capital good with unique characteristics in terms of the embedded labour productivity, energy efficiency, and environmental friendliness. To do so, the firm uses a unique Leontief production technique characterised by a specific set of technical coefficients, with labour and energy as inputs. Capital good vintages and production techniques are both subject to endogenous technological change.

K-firms receive orders for capital goods from C-Firms and produce on demand. Their demand for energy and labour, as well as the emissions arising from the production of capital goods, are computed based on K-Firms' current production techniques. K-firms set the price of the capital goods they produce by applying a fixed and homogeneous markup over unit cost of production. Since K-Firms' production techniques are heterogeneous, so are their unit costs and hence the selling prices of capital goods.

All K-Firms begin each simulation with an equal number of C-Firm customers, but subsequently compete to attract additional ones by sending brochures to C-Firms, which detail both the selling price and characteristics of the capital goods offered. Every C-Firm can switch to a new supplier of capital goods in every period, using the attractiveness measure described in Section 4.3 to compare brochures.

K-firms aim to improve their production technique and to offer improved vintages of capital goods through innovation of new technologies and imitation of technologies of competitors. The process of technological change, drawing on the work of Nelson and Winter (1982) and Dosi (1988), consists of two steps. First, K-Firms allocate resources for innovation and imitation, investing a fixed fraction of revenues into research and development. These resources are used to hire labour and split between efforts directed towards innovation and imitation. The size of these R&D investments determines the likelihood of innovation and/or imitation being successful, i.e. the probability for a given K-Firm to innovate/imitate in some period t is increasing in the respective R&D inputs, $RD_{k,t}^{in}$ for innovation and $RD_{k,t}^{im}$ for imitation:

$$\begin{aligned} P(Innovate)_{k,t} &= 1 - exp\left(-\mathfrak{b}_1^K RD_{k,t}^{in} \right) \\ P(Imitate)_{k,t} &= 1 - exp\left(-\mathfrak{b}_2^K RD_{k,t}^{im} \right) \end{aligned} \tag{2}$$

with $\mathfrak{b}_1^K$ and $\mathfrak{b}_2^K$ being fixed parameters. Conditional on innovation and/or imitation being successful, the characteristics of the resulting technology or technologies are determined stochastically.

Innovation is depicted as a random simultaneous change to all characteristics (labour productivity, energy efficiency and environmental friendliness) of the capital goods produced by, as well as the production technique used by the innovating K-Firm. Importantly, these stochastic innovations need not all be positive, i.e. the innovation process may result in a technology that is worse than the existing one along one or more dimensions. This accounts for the trial-and-error nature of the innovation process.

Imitation, by contrast, is based on a measure of technological proximity, derived by comparing the labour productivities, energy efficiencies and emission intensities of the capital vintages and production techniques of all K-Firms (see Appendix A). K-Firms are assumed to be more likely to imitate the technology of competitors whose technology is more similar to their current one. Here, too, the model allows for the possibility that an imitated technology is inferior to the one already possessed by the imitating firm.

To decide which new technology (if any) to adopt, a K-Firm k compares the innovated and imitated technologies to one another, as well as to its existing technology. To do so, it uses a measure of attractiveness (which is also used by C-Firms in choosing suppliers and deciding on substitution investment; see Section 4.3), which it

Table 4

Model change/extension	Brief explanation
Distinction between net worth and net financial assets for C-Firms; tracking nominal value of capital stocks and inventories	Stocks of capital and inventories were previously tracked as physical quantities. Their inclusion in the balance sheet at nominal value enables correct distinction between net financial assets (deposits minus loans) and net worth (assets minus liabilities)
K-Firms linked to banks as deposit holders	K-Firms are now formally and consistently linked to the banking sector to receive payments from C-Firms; see also Pallante et al. (2024, forthcoming).
Banks' balance sheet: deposit tracking	Deposits were previously tracked on the asset side for deposit holder, not within the individual banks' balance sheets. Now, payment flows between banks are fully modelled; see also Pallante et al. (2024, forthcoming).
Central Bank balance sheet	Previously only tracked the stock of government bonds held by the central bank, but not stocks of reserves or advances. Now, the balance sheet of the central bank is fully modelled.
Firm exit and entry made stock-flow consistent	New firms replacing failed ones were previously injected 'exogenously' rather than entry being financed by some model agent(s); the stocks of capital exiting the model were not accounted for. The exit-entry process is now fully SFC.
Energy sector balance sheet and accounting; link to banking sector (deposits)	Previously no balance sheet items were modelled for this sector; now all items and payments from/to the sector are modelled and accounted for.
Government refinancing	Inclusion of financing needs to repay existing stock of bonds beyond covering deficits; the balance sheet of the government is now fully modelled.
Stock-flow consistent initialisation	Initialisation was not stock-flow consistent (e.g. stock of initial deposits but no corresponding liabilities) and has been fully amended.
Dividend payments	Firm, energy and bank sectors hoarded all profit. While this is not a consistency issue, it may lead to imbalances. Now, we introduced dividend payout rates (which may still be set to 0 if desired) for C-Firms, K-Firms, banks and energy sector.
Liquidity checks	At many points of the code, payments were made without corresponding liquidity checks, which have been now introduced.
Household saving and consumption function	To achieve a stock-flow consistent firm entry process, firm entry must be financed. This financing is provided by households, who consequently must hold savings. Consumption function has been changed to allow for household savings, consumption out of wealth, as well as different propensities to consume out of different income sources. Consequently, households are linked to the banking sector via deposit holdings.

computes for its existing technology, as well as the innovated and imitated ones:

$$A_{\kappa,t} = p_{k,t} + uc_{\kappa,t} b$$
$$A_{\kappa_{in},t} = p_{in,k,t} + uc_{\kappa_{in},t} b \quad (3)$$
$$A_{\kappa_{im},t} = p_{im,k,t} + uc_{\kappa_{im},t} b$$

where $p_{k,t}$ is the price which k currently charges for one unit of capital good, while $p_{in,k,t}$ and $p_{im,k,t}$ are the prices which k would charge when producing using the innovated or imitated production technique, respectively. The uc terms denote the unit cost of production which C-Firms would incur when using a machine of the current, innovated, and imitated vintage, respectively. b is a fixed and homogeneous payback parameter.[4] The K-Firm chooses the technology for which A takes the lowest value. Note that this technology need not be superior along all dimensions, and the values of the A's also depend on the wage rate, the energy price, and the emission tax rate, and hence economic conditions and the policy environment.

Once K-Firms have produced and sold the capital goods demanded in t, their gross profits are computed. If these are positive, they pay profit taxes at a flat rate. In addition, K-Firms distribute a fixed share of after-tax profits as dividends to households (new, previously no dividend payments). Retained earnings are held in the form of bank deposits, with each K-Firm being a customer of one of the banks in the model (new, K-Firms previously not linked to banking sector). For simplicity, it is assumed that K-Firms cannot borrow from the banking sector.

As explained in the detailed model description in Appendix A, a K-Firm may be unable to fulfil all of its payment obligations for energy input or wages. If this is the case, the firm in question exits the model. K-Firms which lose all of their clients also exit the model. Exiting K-Firms are replaced according to the mechanism described in Appendix A and Section 4.4.

4.3. *Consumption good firms*

The consumption good sector consists of $N2$ individual firms producing a homogeneous final consumption good using capital, labour,

[4] b is defined in terms of units of consumption goods and gives the number of units of consumption good which – in the view of an investing firm – must be produced using a superior technology (i.e. one offering a lower unit cost of production) to justify investing in it.

and energy. The capital stocks of consumption good firms (C-Firms) are heterogeneous in terms of vintages, such that each C-Firm has an individual labour productivity, energy efficiency, and environmental friendliness. Since consumption goods are homogeneous, C-Firms compete for market shares through price and their ability to satisfy demand.

C-Firms' desired production is calculated based on expected demand (which follows adaptive expectations)[5] and desired inventory holdings. If a C-Firms' productive capacity in terms of capital stock is insufficient to carry out the desired production, the latter is scaled back accordingly. In order to expand their productive capacity, C-Firms may invest to expand their capital stock (expansion investment).

As commonly assumed in the ABM literature (Dawid and Delli Gatti, 2018), C-Firms aim to maintain their capacity utilisation at a target level u; for a given desired production $Q^d_{c,t}$, the desired capital stock of firm c, expressed in terms of productive capacity, is hence:

$$\mathfrak{K}^d_{c,t} = \frac{Q^d_{c,t}}{u} \tag{4}$$

Desired expansion investment is then given by the difference between the desired and the current capital stock (net of depreciation) of c if this difference is positive (i.e. we do not allow for disinvestment).

In addition, a C-Firm may decide to replace capital goods which have not depreciated but are technologically obsolete relative to newly available vintages (substitution investment). A detailed description of this procedure is provided in Appendix A.

To pick a capital good supplier, C-Firms compare the brochures they have received (see Section 4.2) as in Dosi et al. (2010) and Caiani et al. (2019). This comparison is made using the same attractiveness measure employed for technology selection in the K-Firms' innovation/imitation process (see Eq. (3)). For a given vintage κ produced by a K-Firm k, this measure is given by

$$A_{\kappa,t} = p_{k,t} + uc_{\kappa,t}b \tag{5}$$

with b being the same payback parameter used in Eq. (3). C-Firm c then chooses the observed supplier of capital goods whose vintage offers the lowest value of A.

C-Firms set the price for their output by applying a mark-up on unit cost of production. Mark-ups are heterogeneous and change as a function of C-Firms' market shares. The unit cost of production is also heterogeneous across C-Firms as it depends on the composition of an individual C-Firm c's capital stock in terms of capital vintages. C-Firm c's effective labour productivity ($Pr^e_{c,t}$), energy efficiency ($EE^e_{c,t}$) and emission intensity/environmental friendliness ($EF^e_{c,t}$) are a weighted average of the labour productivities, energy efficiencies and emission intensities embedded in the various vintages capital goods used by c. Based on these, C-Firms' compute the unit cost to which they apply the mark-up for price-setting and determine their demand for labour and energy, as well as the emissions resulting directly from the production of consumption goods.

C-Firms finance their production and investment using retained earnings, held in the form of bank deposits, and loans from the banking sector. Besides possibly being credit-rationed (see sub-Section 4.5), each C-Firm has an internal constraint giving a maximum amount of credit it is prepared to take on for the purpose of investment, given by a multiple of its net revenue (sales revenue minus production cost) in the previous period. If the nominal value of desired investment exceeds the sum of internal funds and this maximum amount of credit, the C-Firm will scale its investment back accordingly. Additionally, a C-Firm may also be subject to an external credit constraint if its bank is unwilling to extend all the credit that the firm demands (Stiglitz and Weiss, 1981). In this case, too, planned expenditures (possibly also including planned production) must be reduced until they can be financed out of internal funds plus the maximum amount of credit available.

Households' aggregate demand for consumption goods is distributed to C-Firms according to market shares. As the consumption good market is characterised by imperfect information, the market share of each firm follows a quasi-replicator dynamic (cf. Dosi et al., 2010; Reissl, 2020; Pedrosa and Lang, 2021) and is a function of its competitiveness, $E_{c,t}$. The latter is in turn computed based on the firm's price relative to the average across C-Firms $\left(\frac{p_{c,t}}{\hat{p}_t}\right)$ and its relative ability to satisfy the demand received in the previous period $\left(\frac{l_{c,t}}{\hat{l}_t}\right)$ [6]:

$$E_{c,t} = -\left(\frac{p_{c,t}}{\hat{p}_t}\right)^{\omega_1} - \left(\frac{l_{c,t}}{\hat{l}_t}\right)^{\omega_2} \tag{6}$$

Market shares $f_{c,t}$ are then computed using this measure of competitiveness and normalised to ensure that they sum to 1:

$$\tilde{f}_{c,t} = f_{c,t-1}\left(\frac{2\omega_3}{1+e^{\left(-\chi\frac{E_{c,t}-\hat{E}_t}{\hat{E}_t}\right)}} + (1-\omega_3)\right) \tag{7}$$

$$f_{c,t} = \frac{\tilde{f}_{c,t}}{\sum_{i=1}^{N2}\tilde{f}_{i,t}} \tag{8}$$

Note that the functional forms of both $E_{c,t}$ and $\tilde{f}_{c,t}$ are changed relative to previous DSK/K+S versions (cf. Dosi et al., 2010). While the underlying logic is identical, the new functional forms allow for an improved fine-tuning of the weights of the two factors determining competitiveness and the possibility of very large market share losses within single periods (e.g. one large firm losing its entire market share in a single period).

Consumption demand is distributed using the computed market shares over multiple rounds, until either all consumption demand has been satisfied or all C-Firm output has been sold.

To ensure stock-flow consistency, C-Firms' profit is computed taking into account both revenues and expenditures, as well as revaluations of capital and inventory stocks. If profits are positive, firms pay taxes at a flat rate τ^C. Moreover, they distribute a fixed share of post-tax profits as dividends to the household sector (new, previously no dividend payments). In addition to interest payments on loans (which enter the profit calculation), C-Firms must also repay a share of outstanding loans at the end of each period.

C-Firms exit the model if they are unable to make a due payment, if they are unable to roll over outstanding loans, if their market share falls below a fixed lower threshold close to zero,[7] or if their net worth becomes negative.

4.4. Firm exit and entry

Every exiting firm is replaced by a new one operating in the same sector at the end of each period (Bartelsman et al., 2005). The new firm replacement mechanism is designed to ensure stock-flow consistency, with the overall logic following the same lines as Caiani et al. (2016).

When a K-Firm exits, any remaining balance of deposits is transferred to the household sector. The new K-Firm replacing the exiting one receives a transfer of deposits from the household sector. Its initial technology is a random copy of an incumbent in the capital good sector.

When a C-Firm exits, any remaining bank deposits are used to pay off outstanding loans, with the rest being transferred to households.

[5] See Dosi et al. (2020) for an exploration of alternative expectation formation mechanism, showing that the underlying K+S macroeconomic framework is robust to such variations.

[6] The computation of $l_{c,t}$ is described in Appendix A.

[7] Note that the replicator equation used to compute market shares cannot give rise to negative (or zero) market shares, so a lower threshold close to but not equal to zero is defined to denote the point at which a firm exits due to having lost its share in the market.

In addition, the banks may sell the remaining capital stocks of exiting firms on a second-hand market to compensate for losses on remaining unpaid loans. Entering C-Firms receive a transfer of deposits from the household sector. In addition, they receive an initial stock of capital, made up of second-hand capital goods stemming from exiting firms which were previously transferred to households or sold to them by the banks. Appendix A contains details on how entering firms are initialised.

4.5. Banks

The banking sector consists of NB individual banks which differ in the number of individual firm customers, implying that the size and composition of bank balance sheets is heterogeneous. At the beginning of a simulation, each bank is assigned a number of K-Firm and C-Firm customers drawn from a truncated Pareto distribution to produce a right-skewed size distribution (Ennis, 2001, ; partly new, previously only C-Firms were linked to banks). Thereafter, the firm-bank networks remain static unless a bank fails and is not bailed out. While each firm is hence linked to a single bank, the deposit holdings of households and the energy sector (which are aggregates) are distributed across all banks in proportion to the number of firm customers of the respective banks (new, previously no link between banks and households or energy sector).

Deposits held by firms, households and the energy sector are the banks' main liability. The interest rate on deposits is identical across banks and given by a markdown on the central bank deposit interest rate. On the asset side, banks provide loans to C-Firms. The maximum amount of credit a bank b is prepared to extend is given by a multiple of its net worth (e.g., see Delli Gatti et al., 2005; Raberto et al., 2012; Dosi et al., 2013). This 'credit multiplier' changes endogenously as a function of the financial fragility of b, defined as losses from defaults taken in the previous period as a share of net worth. Specifically, the maximum amount of credit supply a bank provides in each period is:

$$\mathfrak{C}^s_{b,t} = \frac{NW_{b,t}}{buffer_{b,t}} \tag{9}$$

where NW represents net worth and $buffer$ a credit multiplier depending on a parameter representing prudential regulation, as well as the bank's financial fragility (see also Appendix A).

Interest rate discrimination based on perceived debtor risk is a common practice in the ABM literature (e.g., see Delli Gatti et al., 2010; Riccetti et al., 2013; Russo et al., 2016). In line with this approach, we adopt a relative risk perspective, where banks rank their C-Firm customers in ascending order based on their debt service to revenue ratio. The loan interest rate charged by bank b to customer C-Firm c is then given by:

$$r^l_{b,c,t} = r^l_{b,t}\left(1 + \left(rank_{c,t} - 1\right)\mathfrak{M}\right) \tag{10}$$

where $r^l_{b,t}$ is a baseline loan rate given by a constant and homogeneous mark-up over the central bank lending rate, $\mathfrak{M}$ is a parameter, and $rank_{c,t}$ is the quartile of the distribution of debt service-to-revenue ratios among b's customers to which c belongs. The bank hence charges a higher loan rate to customers with a higher debt service to revenue ratio. In addition, this ranking is also used in the allocation of loans, with the banks satisfying firm credit demand in the order of the ranking of their customers, meaning that firms with high debt service to revenue ratios are more likely to be credit rationed (Bernanke et al., 1996).

In addition to lending to C-Firms, banks also invest in government bonds, with each bank's demand for government bonds being given by a fraction of its stock of loans to the private sector.

When a bank needs to make an interbank payment, it uses central bank reserves, which it can borrow at the lending rate set by the central bank. Stocks of reserves are remunerated at the central bank deposit rate (new, previously no modelling of interbank payments).

Bank profits are calculated taking into account all interest income and expenditures, as well as possible losses from defaults of C-Firms. If profits are positive, banks pay a fraction τ^B of them in taxes. In addition, they pay a fixed share of profits as dividends to the household sector (new, previously no dividends).

A bank fails if its net worth becomes negative. Depending on the simulation setting, failing banks are either always bailed out by the government (this is the case in the simulations shown in this article) or purchased by the surviving bank with the highest net worth (in this case the government only provides a bailout if that latter bank is unable to purchase the failing one or if there is no surviving bank).

4.6. Government

The government collects taxes on wages, as well as on the profits of firms, banks and the energy sector. These taxes are levied at a flat rate. In addition, the government may collect a carbon tax on firm and/or energy sector emissions which is charged per unit of emission produced and may change at differing rates depending on the simulated scenario (see Appendix A). Note that while such a mechanism can easily be implemented, the DSK-SFC model as shown here does not include a dedicated 'recycling' mechanism for carbon tax revenues. Instead, revenue from carbon taxation enters the government budget in the same way as other tax revenue. Finally, any profits made by the central bank are paid to the government; but central bank losses are also compensated by the government (new, previously no central bank profits/losses modelled).

On the expenditure side, the government pays unemployment benefits to households, given by:

$$UB_t = \zeta w_t\left(LS_t - L_t\right) \tag{11}$$

where w_t is the current nominal wage rate, ζ is a parameter, and $\left(LS_t - L_t\right)$ is the difference between the total labour force and the amount of labour employed in t. As explained in Appendix A, the government may also have expenditures to finance the entry of new firms (if households are unable to finance entry) and for bailing out failing banks.

Additionally, the government must make interest payments on the stock of outstanding government bonds. The interest rate on government bonds is determined by marking down the central bank lending rate.

Finally, in every period, the government must repay a share of outstanding government bonds (but can repay more if it has a sufficiently large surplus).

If tax revenues are insufficient to finance all payments the government must make, it issues new bonds to cover the difference. These bonds are in the first instance offered to banks, with any unsold remainder being purchased by the central bank.

4.7. Central bank

The central bank conducts monetary policy by setting the base interest rate. Its lending rate follows a Taylor rule (Taylor, 1993) of the form:

$$r^l_{CB,t} = max\left(\underline{r},\ \iota_1 r^l_{CB,t-1} + \left(1-\iota_1\right) \times \left(r + \iota_2\left(\pi^a_t - \pi^*\right) + \iota_3\left(U^* - U_t\right)\right)\right) \tag{12}$$

where ι_1 is an interest rate smoothing parameter, r is a fixed intercept, π^a_t is the current year-on-year inflation rate with π^* being the year-on-year inflation target, U_t being the current unemployment rate and U^* the central bank's target unemployment rate. $\underline{r}$ is a fixed lower bound close to 0. The central bank's deposit rate is given by a fixed percentage markdown on the lending rate.

In addition, the bank can be thought of as the prudential policy-maker setting the banks' capital requirement as detailed in Appendix A. The central bank also enables interbank payments by supplying the reserves required to settle such transactions. All inflows and outflows of reserves occurring for each bank during a period are recorded to calculate net flows at the end of a period. Banks recording a net outflow either use existing stocks of reserves to cover this or take advances from the central bank, which the latter provides on-demand at the current lending rate by creating them (new, previously no modelling of central bank reserves or advances). We do not model an interbank market for reserves. As noted in sub-Section 4.6, the central bank also acts as a buyer of last resort for government bonds, creating reserves to purchase any bonds not demanded by the banking sector.

4.8. Energy sector

The energy sector consists of a single agent which sells energy to K-Firms and C-Firms. Energy is produced using both 'green' and 'brown' technologies of various vintages.

We assume that the total amount of energy produced is always demand-determined and the energy sector can instantaneously expand its productive capacity by erecting new energy plants to meet demand if necessary. The productive capacity of the energy sector, $\mathfrak{K}_{e,t-1}$, is expressed in units of energy producible and can be divided into 'brown/dirty' $\left(\mathfrak{K}^{de}_{t-1}\right)$ and 'green/clean' $\left(\mathfrak{K}^{ge}_{t-1}\right)$ capacity. Green and brown energy technologies are highly stylised. Brown energy production gives rise to emissions while green energy production does not. Energy production using green technologies is assumed to be costless, while brown energy production requires a costly fossil fuel input, as well as incurring the carbon tax if one is implemented. Conversely, the expansion of brown energy capacity is assumed to be costless, while green energy capacity expansion carries a positive cost.

When expanding capacity, the energy sector must choose whether to invest in green or brown capacity, considering only the most recent vintage of each technology. To do so, it compares the cost of production of one unit of brown energy using the most recent vintage to the cost of installing one unit of green capacity, divided by a payback period parameter. The actual composition of investment carried out then depends on the simulation setting (e.g. the maximum per-period green capacity expansion can be exogenously constrained or not, or investment shares in green and brown technologies can be completely exogenously fixed, see Appendix A).

If the energy sector invests in green capacity, the cost for this takes the form of labour input which is hired from the household sector at the current wage rate. The cost is staggered over the payback period b^e of the investment, but the constructed capacity comes online instantaneously. The model is calibrated such that the energy sector can always internally finance capacity expansion. All energy production plants are assumed to have a fixed lifetime of $\aleph^E$ periods after which they are written off and scrapped.

When producing energy, plants of different technologies and vintages are activated following a 'merit-order' principle (Sensfuß et al., 2008). Since the production cost for green energy is assumed to be zero, green plants are always activated first. If the existing green capacity is insufficient to satisfy all energy demand, brown plants are activated starting from the one with the lowest unit cost of energy production. The uniform price of energy is determined as a mark-up ($\mu_{e,t}$) over the unit cost of energy production of the last plant activated ($mc_{e,t}$):

$$p_{e,t} = \mu_{e,t} + mc_{e,t} \tag{13}$$

where $\mu_{e,t}$ is assumed to grow over time following a weighted average of past changes in the nominal wage to keep the energy price in line with the nominal size of the rest of the economy.[8] Note that when energy production is carried out exclusively by green technologies we have $mc_{e,t} = 0$. Therefore an additive markup in the price equation ensures a positive energy price at all times. If brown energy is produced, the energy sector purchases the required fossil fuel input from the fossil fuel sector (described in sub-Section 4.9) and emissions from energy production are calculated.

Similarly to K-Firms, the energy sector engages in R&D in order to develop new and superior vintages of green and brown energy production technology. Since there is only one agent in this sector, no imitation of technologies takes place and all R&D efforts are directed towards innovation. The energy sector invests a fixed share of its revenue into R&D activities which are divided between research on green and brown technologies either in fixed proportions or endogenously (i.e., either according to the shares of the two technologies in total capacity or current energy production, see Appendix A).

R&D is carried out using labour as an input, and innovation proceeds in similar fashion as for K-Firms. The probability of an innovation taking place in green/brown energy technology is increasing in the amount of R&D activity directed towards the respective technology. Innovations are modelled as random changes to the characteristics of the existing technologies. In the case of brown energy, the new technology is characterised by a different fossil fuel input requirement and emission intensity, i.e. a different unit cost of energy production. In the case of green technology, innovation takes the form of a different unit cost of capacity expansion. As for K-Firms, we allow for the possibility of an innovated technology to be inferior to the current one, in which case it is not adopted.

Having carried out investment, production and R&D activities, the energy sector calculates its profit and pays a fixed share of positive profits as dividends to the household sector (new, previously no dividends). Retained earnings are held in the form of bank deposits, distributed across all banks in the same way as household deposits (new, previously no link to banks).

4.9. Fossil fuel sector

The present version of the model adds a simplified separate fossil fuel sector which sells fossil fuels as input to the energy sector. It is modelled in such a way that it can largely be separated from the rest of the model to mimic an external fossil fuel supplier when the model is calibrated to represent a single region (e.g., the European Union; see Kremer et al. (2024) for an application making use of this simplified sector to simulate external energy price shocks).

The sector is not connected directly to the commercial banking system but instead holds a non-remunerated reserve account at the central bank which it uses to make and receive payments. This may be thought of as a simplified depiction of international payments, whereby payments for the fossil fuel input are cleared through the domestic central bank, giving rise to a liability of the central bank towards the 'foreign' sector. The fossil fuel sector sells a costlessly produced fossil fuel at a price which in every period is updated in line with the weighted average of past changes in the nominal wage rate which is also used to update the mark-up of the energy sector, to keep the fossil fuel price in line with other nominal quantities unless otherwise specified. Given that the fossil fuel sector has zero cost, its revenue coincides with its profit, which is added to its reserve balance. To ensure that its stock of wealth feeds back on a flow in the model (cf. Nikiforos and Zezza, 2017), it pays a fixed share δ^F of its accumulated wealth to households in every period. By setting δ^F to a very small (but positive) value, it can be ensured that payments from the fossil fuel sector have a very limited effect on the rest of the model.

[8] Assuming that the growth rate of $\mu_{e,t}$ is tied to past changes in nominal wage essentially amounts to assuming that for a given (average) energy efficiency, the share of the energy sector in national income is relatively stable rather than constantly growing or shrinking.

4.10. Climate

The model incorporates two climate modules between which the user can switch. Both are calibrated to run at annual frequency. If the economic parts of the model are calibrated to run at quarterly frequency, the activated climate module is called every four periods.

The emissions being used as inputs for the climate module can either be all endogenous (if the economic model is calibrated to the global level) or partly exogenous (if the economic model is calibrated to some region). In the latter case, exogenous ('rest of the world') emissions follow a fixed growth rate set as a parameter and are added to endogenous emissions to be used as an input for the activated climate module. As outlined in the previous sub-sections, endogenous emissions arise both directly from the production of capital and consumption goods (process-emissions) and from the production of energy by the energy sector. Emissions are hence both a direct and an indirect function of the production of final output, since the production of energy is driven by firms' demand for energy.

The simpler climate module is based on cumulative emissions (cf. Matthews et al., 2009, 2012), deriving a global temperature anomaly as:

$$Temp_t = \Upsilon_1 + \Upsilon_2 \mathcal{E}_t^{\Sigma} \tag{14}$$

where $\mathcal{E}_t^{\Sigma}$ are cumulative emissions up to period t.

The more complex climate module, based on Sterman et al. (2013), depicts a carbon cycle in which the atmospheric carbon content depends on anthropogenic emissions and carbon exchange between the atmosphere, oceans and biomass. Via several steps described in detail in Appendix A, the module derives the heat content and temperature anomaly of ocean layers, with the global temperature anomaly being assumed equal to that of the top ocean layer.

Whichever climate module is active in a given simulation will return a global temperature anomaly which forms the basis for the determination of climate impact shocks. These shocks may enter the model economy through various channels at the micro- and macroeconomic level depending on simulation settings. Among others, model allows for a simulation of climate impact shocks to current output, capital stocks, productivity and R&D effectiveness, individually or jointly, with a range of specifications. A full description of all shock channels and specifications is provided in Appendix A.

When shocks through some channel s are determined directly at the individual agent level, we posit that they are drawn for each agent in each period from a beta distribution:

$$shock_t^s \sim Beta\left(S_{1,t}^s, S_{2,t}^s\right), \tag{15}$$

The shape parameters of this distribution are a function of the temperature anomaly, being given by

$$\begin{aligned} S_{1,t}^s &= S_{1,0}^s \left(1 + ln\left(\frac{Temp_{t-1}}{Temp_0}\right)\right)^{\Upsilon_3^s} \\ S_{2,t}^s &= S_{2,0}^s \left(\frac{Temp_0}{Temp_{t-1}}\right)^{\Upsilon_4^s} \end{aligned} \tag{16}$$

where $\Upsilon_3^s > 1$ and $\Upsilon_4^s > 1$. This implies that as the temperature anomaly increases, the mode of the distribution will shift upwards and the right tail of the distribution will become thicker, reflecting an increased frequency of extreme events (Katz and Brown, 1992). When aggregate shocks are required, we assume that these are given by the current mean of the beta distribution defined in Eq. (15).

5. Code upgrades

In addition to the incorporation of a comprehensive accounting system to ensure stock-flow consistency, another major emphasis during the development of DSK-SFC has been on the usability and accessibility of the model code, with a view to lowering the entry cost for researchers interested in applying the model and enhancing the reproducibility of results. Here, we briefly outline the main upgrades which were made to the code in this respect.

- As for previous versions, the model code is written in C++ and compiled using CMake. For this version, we ensured that the model can be compiled and simulated out of the box on all common operating systems (Linux distributions, Windows, macOS).[9]
- Large amounts of unused legacy code have been removed, commenting has been improved and the code has been thoroughly cleaned to ensure easy readability.
- Parameters, initial values and flags were previously defined as global constants, with values hard-coded into the model scripts. They could hence not be changed at runtime. Parameters, initial values and flags are now externally supplied through a *.json* file and their values can be changed at runtime. Experiments can hence be performed without having to recompile the model executable.
- When invoking the model executable file through the command line, the user can now specify a range of arguments, including the path to the input file, a name for the run to be appended to all output files, and most importantly the seed for the pseudo-random number generator which was previously set in a loop within the model code itself. This in turn allows for the model executable to be called e.g. through a shell, Python or R script with different seeds on different cores, hence enabling the implementation of parallel model runs e.g. for calibration or large simulation experiments.
- The model code includes an increased number of checks for errors (e.g. variables that should be strictly positive but may become zero or negative when unusual parameter combinations are supplied) and unusual/undesired behaviour (e.g. households not being able to finance firm replacement), as well as exit conditions leading to a cancellation of degenerate runs. Additionally, the model code performs an extensive and rigorous set of stock-flow consistency checks and generates a warning if violations occur (e.g. as a result of model extensions which lead to a violation of accounting rules). All registered errors and warnings are recorded in a dedicated log file including the name of the run, the seed and the period in which an error or warning occurred to allow for easy reproducibility and tracing of the causes.

The next section briefly describes the model initialisation and calibration procedure followed in this paper.

6. Calibration and validation

The changes to the model made in the context of the introduction of the stock-flow consistent accounting structure necessitate a recalibration, as the updated model does not produce qualitatively reasonable dynamics using calibrations from pre-SFC versions. In addition, the initialisation procedure must be made stock-flow consistent to produce a set of initial conditions which do not violate accounting rules.

The initialisation of the model is simplified and similar to what is common with other macroeconomic ABMs in the literature. Initial values are set such that stock-flow consistency is satisfied and to keep the transient/'burn-in' phase of simulations which the model undergoes

[9] While the model can be compiled and simulated on all common operating systems, results of a given individual run may not be identical across machines and operating systems due to differences in the handling of floating point arithmetic. These may arise from the use of different compilers, compiler versions, compiler options, as well as differences in processor architecture. Through test runs on different machines and different operating systems, we have ensured that while results of individual runs for a given seed may exhibit differences, the distributions of results arising from a full scenario simulation (108 different seeds in our case) are almost identical. For precise reproducibility, works making use of the model code should exactly specify the compilation and simulation setup under which specific results were produced.

before converging to its eventual trajectory (and which is discarded in the analysis of model output) as short as possible. The initialisation procedure is described in more detail in Appendix A. That appendix also explains how aggregate variables such as GDP, employment, emissions and the consumption price index are computed and how the checks for stock-flow consistency during simulation are performed. As outlined in the model description (particularly the detailed description given in Appendix A), the model code also contains a number of indicator variables allowing the user to simulate different specifications of certain parts of the model. The specific settings used for the runs shown here are also outlined in Appendix A.

For the calibration of the economic model, we aim to arrive at a *quarterly* calibration under which the (filtered) simulated macroeconomic time-series exhibit qualitatively reasonable business-cycle dynamics broadly in line with quarterly empirical data for the European Union from 2001 to 2020, as detailed in Appendix A. This involves manually calibrating the major parameters responsible for governing the behaviour of the model at business cycle frequency, such as parameters related to wage-setting, firm competition, investment and monetary policy until a satisfactory match with empirical data is achieved. In addition, we calibrate the long-run dynamics of the model such that the average growth rates of real GDP, energy use in industry and emissions broadly match those of a ‘Shared Socioeconomic Pathway 2’ (SSP2) scenario (Riahi et al., 2017) for the European Union from 2010 to 2100. We also make use of these scenarios in order to set the parameters governing the rate of change of the labour supply and the growth of exogenous (rest of world) emissions. For this purpose, we manually calibrate the parameters related to labour supply, labour productivity, energy efficiency and emission intensity growth until a growth path that is both balanced and in line with SSP data is achieved. The parameter values used to construct the simulations shown in this paper are listed in Appendix B. Overall, our approach hence corresponds to the ‘indirect’ calibration method commonly used in agent-based modelling, as described e.g. by Fagiolo et al. (2019), with a recent application being (Delli Gatti and Reissl, 2022). As such, the calibration and initialisation procedure is not as empirical and data-driven as that of large-scale empirical SFC models such as Burgess et al. (2016) or Zezza and Zezza (2022) or the ABM of Poledna et al. (2023). This limitation of the model in accurately representing the economy of the European Union should be kept in mind when interpreting the results presented below.

As the model description indicated, the model code contains a number of indicator variables allowing the user to specify the simulation setting (e.g. the way in which failing banks are handled, the allocation of R&D expenditure in the energy sector, etc.). Appendix A indicates how these variables are set in the simulations shown here. Most importantly, climate impact shocks are deactivated for the baseline run and activated in one of the experiments shown in this article.

In Table 5 we report the main business cycle and growth statistics produced by the model as average values across 108 runs with different reproducible seeds for the pseudo-random number generator.[10] Each of the 108 baseline simulations has a post-transient duration of 400 periods (quarters), i.e. 100 years. The length of the discarded transient is 200 periods. Standard deviations of macroeconomic time series are derived by first applying the Hamilton filter (Hamilton, 2018; Schüler, 2018) to the respective series and then calculating the standard deviation of the cyclical component. Confidence intervals (reported in brackets in Table 5. are calculated across the 108 runs. Empirical business cycle statistics are similarly constructed by applying the Hamilton filter, calculating the standard deviation of the cyclical component, and constructing bootstrapped confidence intervals. Simulated growth rates are calculated on raw quarterly data and then annualised. Growth rate data for SSP-scenarios are taken from IAM scenario data available in the Scenario Explorer and Database for the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Byers et al., 2022), as detailed in Appendix A.

Table 5
Simulated and empirical business cycle and growth statistics.

Description	Sim.	Emp.
Standard deviation of GDP	0.02580 (0.02537, 0.02623)	0.02500 (0.02490, 0.02510)
Standard deviation of Consumption	0.01582 (0.01550, 0.01614)	0.01684 (0.01678, 0.01689)
Standard deviation of Investment	0.15576 (0.15366, 0.15787)	0.04879 (0.04855, 0.04903)
Standard deviation of Employment	0.01981 (0.01951, 0.02012)	0.0088 (0.00875, 0.00884)
Standard deviation of Inflation	0.01649 (0.01624, 0.01673)	0.01630 (0.01627, 0.01634)
Av. ann. GDP growth	0.01305 (0.01293, 0.01317)	0.01233 NA
Av. ann. emissions growth	0.00125 (0.00097, 0.00153)	0.00032 NA
Av. ann. growth of energy use in ind.	0.00110 (0.00086, 0.00134)	0.00022 NA

It can be seen that the model is able to produce reasonable volatilities for GDP, consumption and inflation. Investment, however, is much too volatile relative to GDP, as is common in macroeconomic ABMs. Similarly, the employment rate is too volatile relative to GDP compared to what is typically observed in empirical data. The growth rates of GDP, carbon emissions and energy use in industry are close to what is predicted for the European Union countries in SSP2 scenarios with current policy, with GDP growth being steady but relatively low and growth rates of emissions and energy use in industry being very low.

Fig. 2 plots the simulated and empirical autocorrelation functions of the main macroeconomic time-series, calculated on filtered data (the bands around the lines, which in this and many other figures are almost invisible due to being very narrow, represent 95% confidence intervals). In addition, the figure shows the cross-correlation functions of the main macroeconomic time-series with real GDP. The fit on most autocorrelations appears good. Cross-correlations are generally qualitatively reasonable but the quantitative fit is less satisfactory.

Appendix A contains further figures illustrating the cyclicality of important macroeconomic variables. Making use of the stock-flow consistent accounting structure, it also shows that the sectoral net worth to nominal GDP ratios and sectoral financial balances do not exhibit long-term trends. Furthermore, it plots examples of variables which can be tracked more accurately using the stock-flow consistent structure. Finally, we use the simulated model data to inspect a range of characteristics and qualitative stylised facts (cf. Haldane and Turrell, 2019), as is usually done for models from the K+S family (see e.g. Dosi et al., 2010, 2015, 2017a; Lamperti et al., 2018). The relevant table along with references to the literature can also be found in Appendix A.

The calibration of the global climate modules is identical to that used in previous versions of the DSK model. Exogenous (rest of the world) emissions, calibrated on SSP2 scenarios, are added to endogenous (EU) emissions generated by the economic model and used as an input for the two alternative global climate modules. We perform a small validation exercise on both climate modules by obtaining time-series on emission pathways and temperature anomalies for the period 2010 to 2100 from the IPCC AR6 scenario database (Byers et al., 2022), considering a range of scenarios with different carbon budgets (from 400 up to 3000 $GtCO_2$). We then feed these emission pathways into the climate modules used in our model to confirm that the temperature anomalies predicted by the modules lie within the range of those

[10] The high-performance cluster on which the simulations were carried out features nodes with CPUs containing 36 cores. When performing parallelised simulations, it is therefore efficient to set the number of runs to a multiple of 36. The number of runs performed is in line with – in fact rather at the upper end of – the literature on medium to large-scale macroeconomic ABMs (e.g. Caiani et al., 2016; Delli Gatti et al., 2023).

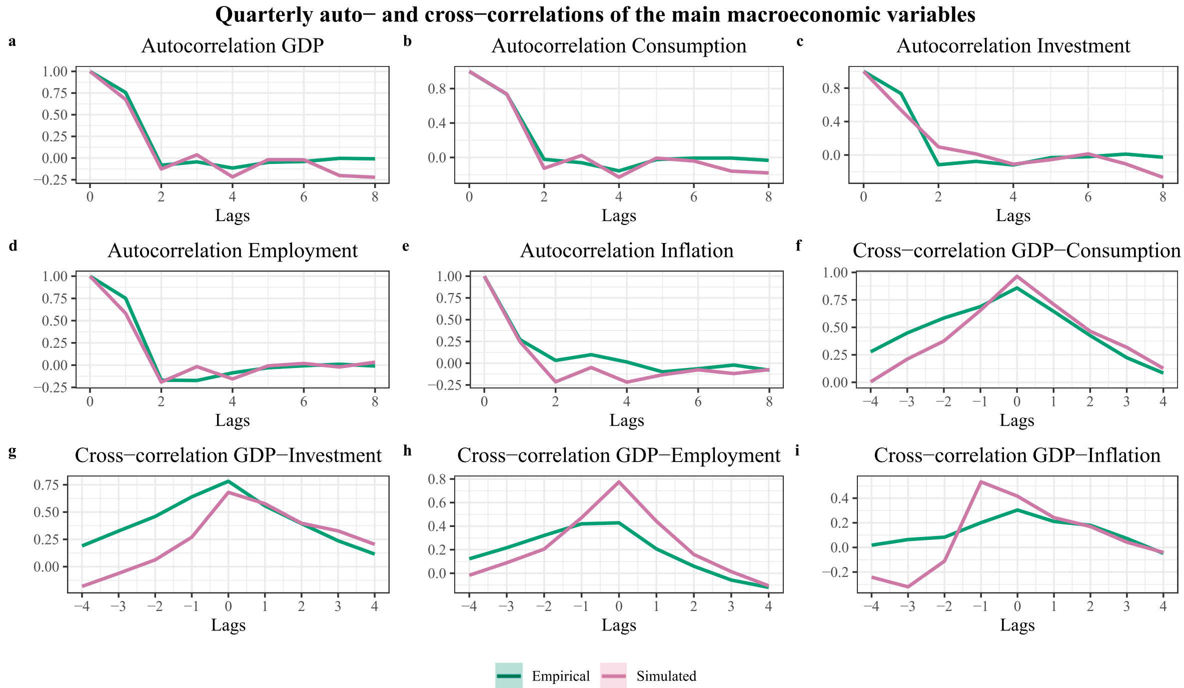

Fig. 2. Panels (a-e): Simulated and empirical autocorrelations of the main macroeconomic aggregates; Panels (f-i): Simulated cross-correlations of real GDP and other macroeconomic aggregates. Auto- and Cross-correlations are calculated on filtered quarterly simulated time-series. Bold lines represent averages across 108 simulations with different seeds for simulated data and bootstrapped means for empirical data. Shaded bands represent 95% confidence intervals.

reported in the scenario database for the scenario in question. This is indeed the case for all scenarios we consider.

Qualitatively, the baseline economic dynamics of the stock-flow consistent version of the DSK model are similar to those of its predecessors. The evolutionary/Schumpeterian process of endogenous technological change gives rise to long-term growth in labour productivity while the presence of a Keynesian, demand driven macroeconomic structure along with the financial sector enables the emergence of business cycle fluctuations. Business cycles are driven by the dynamic interactions between firms' investment decisions, technological progress, credit constraints, and labor market conditions which affect household incomes. C-Firms invest in new machinery to improve productivity (with this investment in turn feeding back on the extent of R&D-activities in the K-Firm sector), but this investment is influenced by expectations of future demand and access to credit from banks. During an upswing, firms invest heavily, boosting production, employment, the level of the wage rate and household income, and thereby aggregate demand. However, when firms face lower than expected demand, they reduce investment and may also experience liquidity shortages, especially when banks limit credit access due to increasing financial fragility. This leads to rising unemployment, declining output and household income and thereby declines in aggregate demand, triggering an economic downturn which may be exacerbated if it is accompanied by the failure of one or more banks. Additionally, technological innovation and diffusion occur unevenly across firms, causing productivity disparities that contribute to fluctuations in output. These endogenous feedback loops between technological change, production, investment, credit, and demand create cyclical expansions and contractions.

Both the production of final output and the production of energy give rise to emissions. Unless technological progress in energy efficiency at least keeps pace with expansions of final output, energy use therefore also increases as the model economy grows. Similarly, emissions from the production of final output will grow unless technological progress in emission intensity is sufficiently swift. The energy sector itself can reduce its emission intensity either by investing in green technologies or by gradually reducing the emission intensity of brown ones through technological progress. In line with the IAM scenarios used in the calibration process, the parameters governing the pace of technological progress in energy and emission intensity are set to produce roughly constant energy use and emissions in the baseline.

The reactions of the recalibrated DSK-SFC model to the simulation experiments shown in the next section are similar to those produced by previous versions of the DSK model when these were subjected to similar experiments. Nevertheless, the addition of an SFC structure gives the results of simulation experiments an increased degree of reliability since any potential biases arising from violations of accounting rules are avoided. This is particularly true for financial variables, stock-flow ratios and bankruptcy or bank failure statistics, some of which are analysed in the experiments shown in the next section but in our view also extends to others since virtually every variable in the model either directly or indirectly depends on one or more balance sheet items or transaction flows.

7. Simulation experiments

To provide some example scenarios, we conduct several simulation experiments featuring climate policy, climate change impacts, as well as changes in macroeconomic policy [11]:

- A scenario with a higher carbon tax on the energy sector than in the baseline.
- A scenario with climate shocks to C-Firms' capital stocks, and one with shocks to both labour productivity and energy efficiency.

[11] The calibration and simulation runs shown in this paper were produced on the 'Zeus' High-Performance Cluster of the Euro-Mediterranean Center on Climate Change (CMCC), running Linux CentOS 7.6 x86_64 on compute nodes with Intel Xeon Gold 6154 CPUs. Results were subsequently reproduced on the corresponding author's computer running Ubuntu 20.04.4 LTS in WSL2 on an Intel Core i7-1165G7 CPU. The executable was compiled on the corresponding author's computer using GNU GCC 9.4.0.

• Two scenarios in which the unemployment benefit ratio is increased by two different amounts w.r.t. the baseline.

Note that we implement rather standard experiments, as our goal is to illustrate the behaviour of the model in relatively commonly examined types of scenarios rather than to examine innovative policy interventions or derive novel results. We believe that our choice of experiments does a good job at giving an impression of how the model reacts to various types of interventions. The following subsections outline the results of these exercises, also emphasising how the SFC structure aids in producing more reliable results particularly for financial variables. Appendix B contains a series of experiments featuring alternative climate policies.

7.1. Carbon tax

In the baseline scenario; we assume a carbon tax on energy sector emissions, $\tau_t^{Em,E}$, which grows with nominal GDP starting from an initial value. This tax is re-set at an annual frequency, i.e. every four simulation periods. At the beginning of a period in which the carbon tax is adjusted, it is set as follows:

$$\tau_t^{Em,E} = \tau_0^{Em,E} \frac{GDP_{t-1}^n}{GDP_0^n} \tag{17}$$

where GDP^n denotes nominal GDP and $\tau_0^{Em,E}$ is the initial value of the tax. In the simulation experiment, we examine the effect of a sharp increase in the carbon tax on the energy sector. In particular, we assume that in the first four post-transient simulation 'years', the tax doubles every year (i.e. every four simulation periods), and subsequently continues to grow with nominal GDP as shown in Eq. (17). To illustrate the experiment, Fig. 3 plots the amount of carbon tax paid by the energy sector in each period as a percentage of the cost of energy paid by firms (=revenue of the energy sector), both in the baseline and the high tax scenario. The plot shows that the high tax scenario implies a sharp increase in the carbon tax as a share of the cost of energy to firms, beginning around 7% compared to around 3.8% in the baseline (as the first increase takes place in the first post-transient period) and quickly reaching a share of over 33% before beginning to decline as a consequence of the gradual expansion of green energy capacity. Scenarios featuring high and fast-increasing carbon prices are not uncommon in deep decarbonisation scenarios depicted by conventional IAMs (see e.g. Rogelj et al., 2018), meaning that it may be useful to examine their implications in alternative frameworks.

Panel a of figure Fig. 4 shows the effect of this experiment on the energy price in the model. The bold lines represent averages across 108 simulations with different seeds while bands (which are too narrow to be visible in some plots) represent 95% confidence intervals. Recall from the description of the energy sector that the energy price is determined by the infra-marginal cost of energy production, to which a mark-up is added. The former is zero for green energy and positive for brown energy. As long as any brown energy capacity exists and is used to produce energy, a higher carbon tax will be fully passed on to the price of energy, meaning that the latter increases sharply as the shocks to the tax rate take place, and subsequently continues to grow in line with the baseline price.

Panel b of Fig. 4 shows that the share of green energy in the total productive capacity of the energy sector grows gradually, while it remains at the exogenously imposed lower bound of 20% in the baseline. The baseline carbon tax is deliberately calibrated such that it does not lead to green energy becoming cheaper than brown energy and endogenous R&D also does not lead to such a cost advantage in the calibration shown here. The higher carbon tax, by contrast, does confer a cost advantage to green energy technology, which subsequently becomes the preferred option for investment in the energy sector. However, the share of green energy still expands at a relatively slow pace, only reaching a level of just under 60% by the middle of the simulation and around 85% by the end. This is due to the assumption of an exogenous upper bound on the per-period expansion of green energy capacity. Appendix B shows an experiment in which we relax this assumption and also examine alternative climate policies. Panel c of Fig. 4 shows that the higher carbon tax affects *endogenous* emissions (exogenous 'rest of the world' emissions are of course not affected by the experiment), which decline by over 50% relative to the baseline by the end of the simulation. Since only the energy sector is subject to the tax, the decline in emissions is almost entirely due to reduced emissions from that sector. This reduction is in turn chiefly driven by the build-up of green energy production capacity, but as Panel d of Fig. 4 shows, the demand for and hence production of energy also declines relative to the baseline. Initially this is due to the decline in GDP associated with the increase in the carbon tax (see Panel e of 4), but energy demand continues to decline relative to the baseline even as GDP gradually recovers, since the higher energy price incentivises C-Firms and K-Firms to adopt more energy efficient technologies, reducing the energy intensity of GDP. Due to its impact on endogenous emissions, the higher carbon tax also affects the simulated temperature anomaly. However, this effect is extremely limited due the fact that, under the calibration shown here, the vast majority of emissions are exogenous (representing rest of the world, i.e. non-EU emissions not subject to the modelled carbon tax).

Panel e of Fig. 4 shows that a sharp increase in the carbon tax has significant implications for macroeconomic performance, in line with previous versions of the model (Lamperti et al., 2020; Lamperti and Roventini, 2022). GDP decreases strongly on impact and recovers only very gradually, remaining below its baseline value at the end of the simulation. At the same time, the ratio of government debt to nominal GDP (shown in Panel f of Fig. 4) tends to increase. While the additional revenue from the carbon tax by itself does improve the budget balance, this is more than outweighed by the declines in other tax revenue and increases in outlays for unemployment benefits which result from the decline in GDP. Indeed, Panel b of Fig. 6 shows that under the higher carbon tax, the average unemployment rate is significantly higher than in the baseline scenario. Panel a of the same figure also indicates that the higher carbon tax tends to increase the volatility of GDP. As is common in macro-ABMs in general and the K+S model family in particular (cf. Dosi et al., 2017a), the updated DSK-framework appears to feature a high fiscal multiplier. The direct pass-through of the carbon tax into the price of energy and subsequently the price of final output leads to a strong reduction in the purchasing power of households' wage income, which in turn induces a sharp recession during which general revenues from other taxes decline and outlays on unemployment benefits increase, resulting in an increase in the government debt ratio.

Making use of the newly added SFC structure, which ensures an accurate tracking of assets and liabilities, Fig. 5 plots the changes in sectoral net worths as a percentage of nominal GDP which arise as a consequence of the high carbon tax scenario compared to the baseline. As already indicated by Panel f of Fig. 4, the impact of the high carbon tax is chiefly reflected in a lower government net worth, which is now tracked reliably due to the consistent overall accounting structure. In addition, the position of C-Firms deteriorates slightly in the medium run as a consequence of a higher energy price and lower sales. Since the energy sector engages in infra-marginal cost pricing, the high carbon tax induces a large profit windfall on green energy production. Most of this is distributed to households in the form of dividends ((cf. Fierro et al., 2024) which shows that high carbon taxes imply a functional redistribution away from wage income). Since, in contrast to earlier versions of the model, households in the stock-flow consistent model do not consume the entirety of their income but instead generate savings, with the propensity to save out of dividend income being higher than that out of wage income, the functional redistribution induced by the high carbon tax represents an additional drag on the economy. This feedback channel stemming from the SFC structure exacerbates the

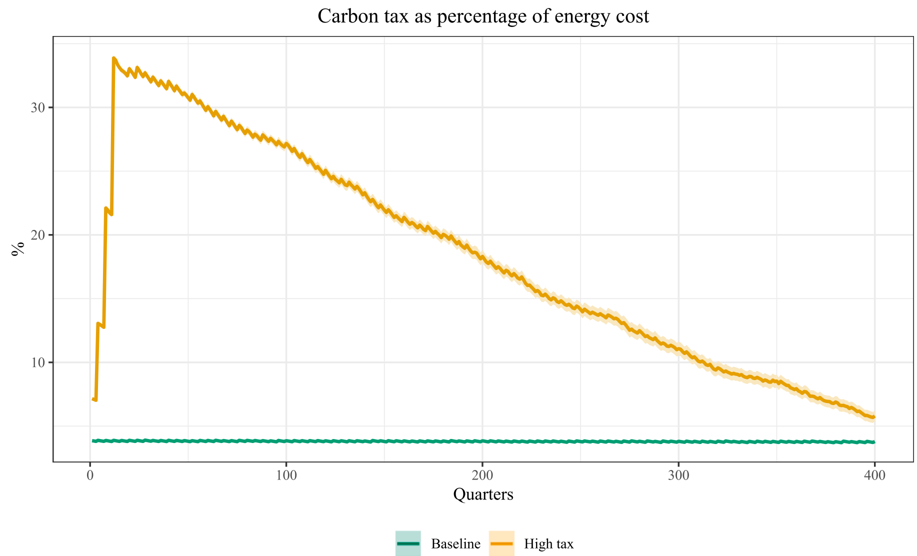

Fig. 3. Carbon tax payments by the energy sector as percentage of the cost of energy paid by firms in the baseline and the high carbon tax scenario. Bold lines represent averages across 108 simulations with different seeds. Shaded bands represent 95% confidence intervals.

output losses generated by the high carbon tax and leads to a very slow recovery of real GDP and employment (therefore also putting additional downward pressure on energy demand), as well as higher government debt. As a consequence of the high carbon tax, the energy sector's net worth also increases steadily as a share of GDP. Banks and K-Firms appear largely unaffected by the experiment.

Panels c to f of Fig. 6 examine the effects of the high carbon tax scenario on the average growth rate of real GDP, splitting the simulation into four phases of 100 periods. The figures indicate that the higher tax has a slightly negative effect on growth initially, while GDP subsequently grows slightly faster during the prolonged recovery phase (without, however, allowing the level of real GDP to fully catch up with its baseline value, as shown in Panel e of Fig. 4).

Overall, these results indicate that carbon taxation can play a role in promoting green transitions, but that it may also lead to substantial transition risks (Lamperti and Roventini, 2022; Känzig, 2023) which are exacerbated when taking into account effects on the functional distribution of income and balance sheets. Recall from the model description that the model as described here does not include a 'recycling' mechanism whereby carbon tax revenue is directly redistributed to households or firms. In an application of the model (Fierro et al., 2024), we show that the macroeconomic costs of carbon taxation can be effectively – though possibly not fully – mitigated through well-designed carbon revenue recycling schemes.

7.2. Bottom-up climate damages

Previous versions of the DSK model have been used to study the macroeconomic relevance of disaggregated, micro-level climate change impacts (Lamperti et al., 2018, 2019a). Building on such exercises, we illustrate the impact of climate change by simulating climate impacts through two channels: shocks to C-Firms' capital stocks and shocks to the labour productivity and energy efficiency of K-Firm production techniques and capital good vintages. In both scenarios, shocks are endogenously determined. As described in Section 4.10 the beta distribution from which shock values are drawn changes as a function of the global temperature anomaly.

Capital stock shocks follow specification 1 outlined in Appendix A: a shock $shock^{cap}_{c,t}$ is drawn from the relevant beta distribution for each C-Firm c in each period. Firm c then loses a share $shock^{cap}_{c,t}$ of its capital stock prior to carrying out production in t. Shocks to labour productivity and energy efficiency follow specification 3 outlined in Appendix A: for each K-Firm k, two shocks ($shock^{lp}_{k,t}$ and $shock^{ee}_{k,t}$) are drawn from the relevant beta distribution in each period. The labour productivity and energy efficiency of k's production technique as well as those of all capital good vintages currently and previously produced by k are then reduced by percentages given by $shock^{lp}_{k,t}$ and $shock^{ee}_{k,t}$, respectively. Table 6 illustrates how the two shock channels are initialised and parametrised, while Figure 19 in Appendix B shows how the shock distributions evolve as a function of the global temperature anomaly. Note that productivity shocks are initially smaller and less dispersed than capital stock shocks by a large margin, and the shape parameters change much more slowly with the temperature anomaly.[12]

Table 6
Initial values and parameters for climate shock scenarios.

Description	Capital stock shocks	Productivity shocks
Initial value shape param. 1 ($S^s_{1,0}$)	1	0.005
Initial value shape param. 2 ($S^s_{2,0}$)	100	1000
Exponent Y^s_3	3	0.25
Exponent Y^s_4	8	0.25

Despite the fact that productivity shocks are calibrated to be much smaller and to grow more slowly with temperature than capital stock shocks, Panel a of Fig. 7 shows that they nevertheless have a dramatic effect on GDP. While the long-term trajectory of real GDP is largely unaffected by capital stock shocks, productivity shocks have a pronounced growth effect which leads GDP to diverge from the baseline trajectory, predicting much larger physical risks from unmitigated climate change than what mainstream, equilibrium-based models usually suggest (Lamperti and Roventini, 2022; Stern et al., 2022). Panel b of Fig. 7 shows the global temperature anomaly resulting from the baseline and the three shock scenarios. In the baseline scenario, the temperature anomaly arrives at just above 3.25 Degrees Celsius at the end of the simulation, and climate impact shocks do not have a significant impact on this trajectory.[13]

To understand the radically different effects on GDP, note that the productivity and energy efficiency shocks directly impact the labour

12 There is in our view no reason to believe that climate impacts through different channels should have the same magnitude or evolve similarly over time. As shown in this sub-section, shocks to productivity exert their effect chiefly through slowing down the growth rate of productivity, meaning that

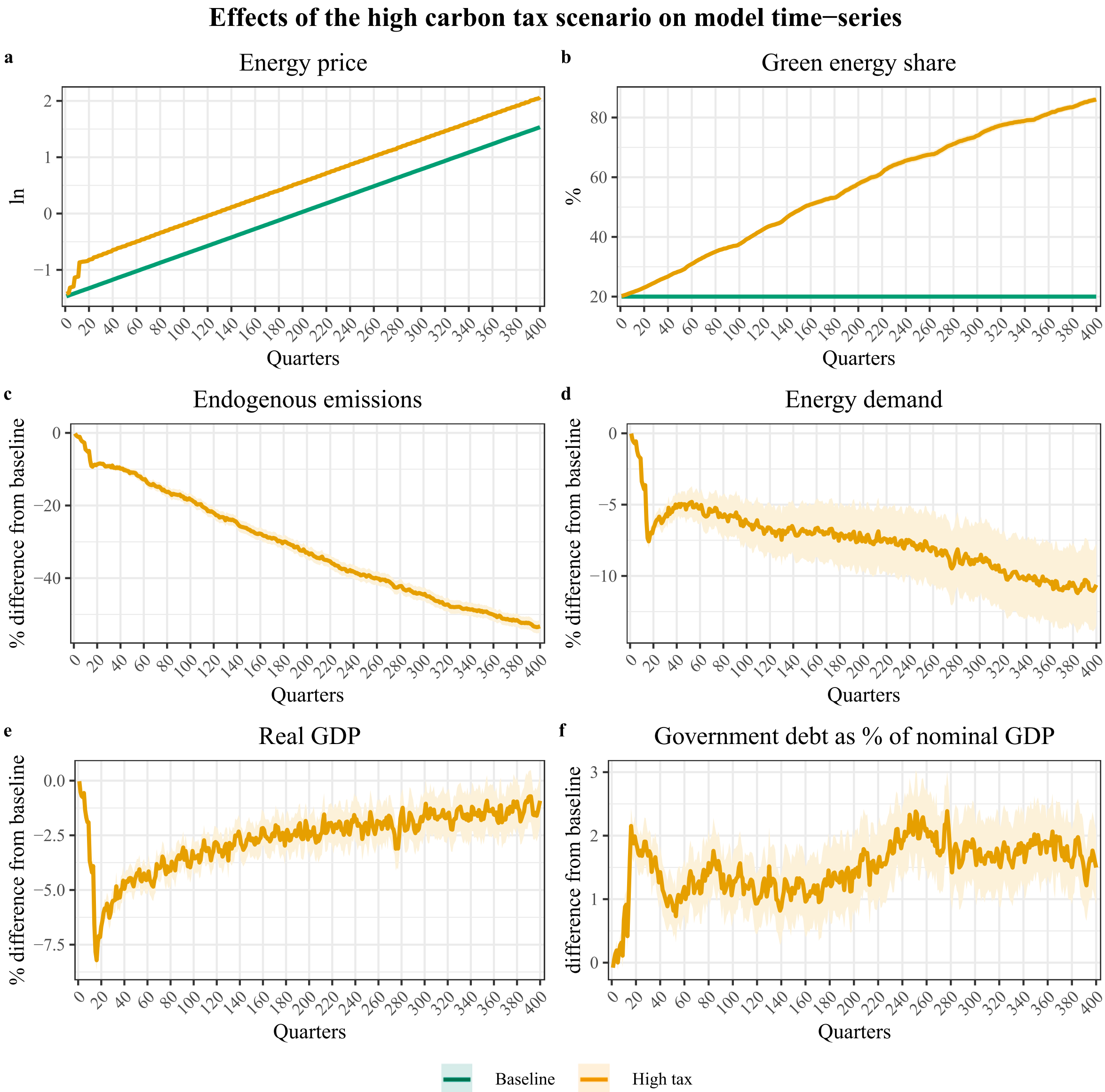

Fig. 4. Panel (a): Natural logarithm of the energy price in the baseline scenario and the carbon tax experiment; Panel (b): Share of green energy capacity in total productive capacity of the energy sector in the baseline scenario and the carbon tax experiment; Panel (c): Endogenous per-period emissions in the carbon tax experiment, as % difference from the baseline; Panel (d): Per-period demand for energy from the firm sectors in the carbon tax experiment, as % difference from the baseline. Panel (e): Real GDP in the carbon tax experiment, as % difference from the baseline; Panel (f): Government debt as percentage of nominal GDP, difference from the baseline. Bold lines represent averages across 108 simulations with different seeds. Shaded bands represent 95% confidence intervals.

productivities and energy efficiencies of all existing vintages of capital goods and K-Firm production techniques. The shocks are hence inherently persistent and compounding. In addition, by affecting the process of technical change and innovation diffusion, they hamper the underlying forces of growth in the model. This explains why even a series of stochastic shocks which is strongly concentrated at very small values may, over time, induce a sizeable decline in GDP growth. Such results call for a much deeper understanding of how climate change may affect productivity advancements and innovation diffusion.

Indeed, Panel b of Fig. 8 shows that in the productivity shock scenario, the average growth rate of real GDP is significantly lower than in the baseline. Panel a of Fig. 8 shows that under shocks to capital stocks, the volatility of filtered real GDP tends to increase relative to the baseline, indicating more pronounced fluctuations at business cycle frequency. Panel b of Fig. 8 also suggests that the average growth rate of real GDP over the entire post-transient simulation is very slightly higher in the presence of capital stock shocks. This is due to attempts by C-Firms to replace the capital stocks destroyed by climate shocks, which leads to additional investment demand, employment and household income which in turn feeds back on consumption demand and the desired production of C-Firms. In the scenario considered here, this leads to a temporary increase in the average growth rate of GDP. Panels c to f of Fig. 8 split simulations up into four phases of 100 periods, showing that the increase in GDP growth induced by capital stock shocks is largely limited to the first three phases, while in the last phase,

even small shocks can give rise to large cumulative impacts (Burke et al., 2015).

[13] Recall that, just as in the carbon tax experiment, exogenous rest of the world emissions are unaffected by anything taking place in the scenarios. In addition, as shown in this sub-section, endogenous emissions do not change much in the shock scenarios relative to the baseline. As such, temperature trajectories are practically identical, making the trajectories of the climate shocks directly comparable.

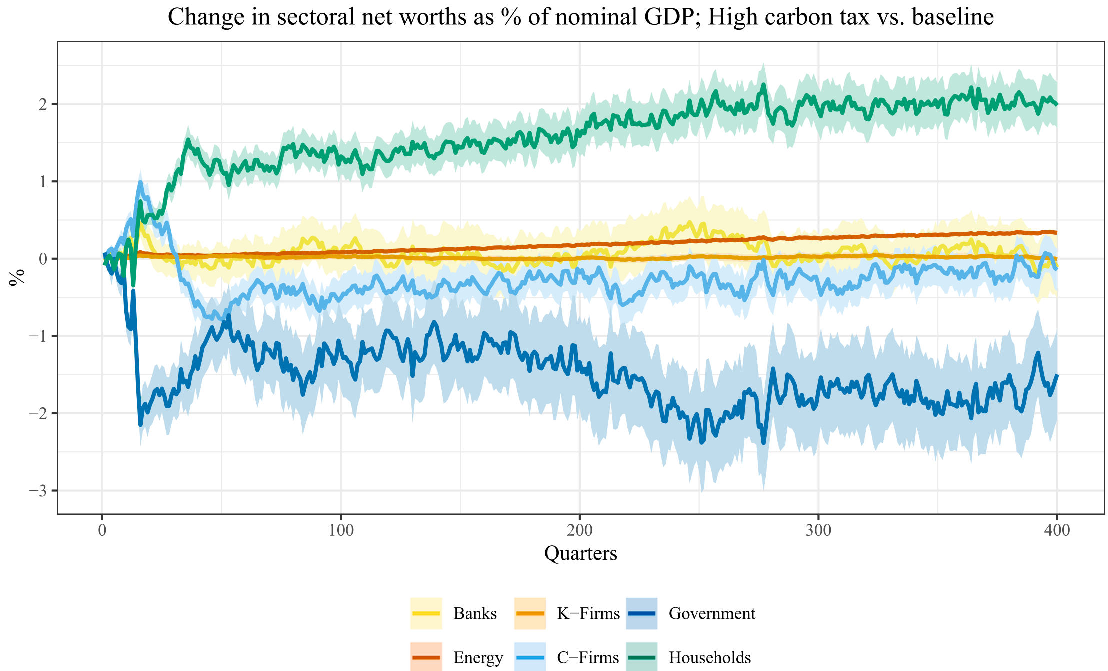

Fig. 5. Sectoral net worths as percentage of nominal GDP, difference between high carbon tax and baseline scenarios. Bold lines represent averages across 108 simulations with different seeds. Shaded bands represent 95% confidence intervals.

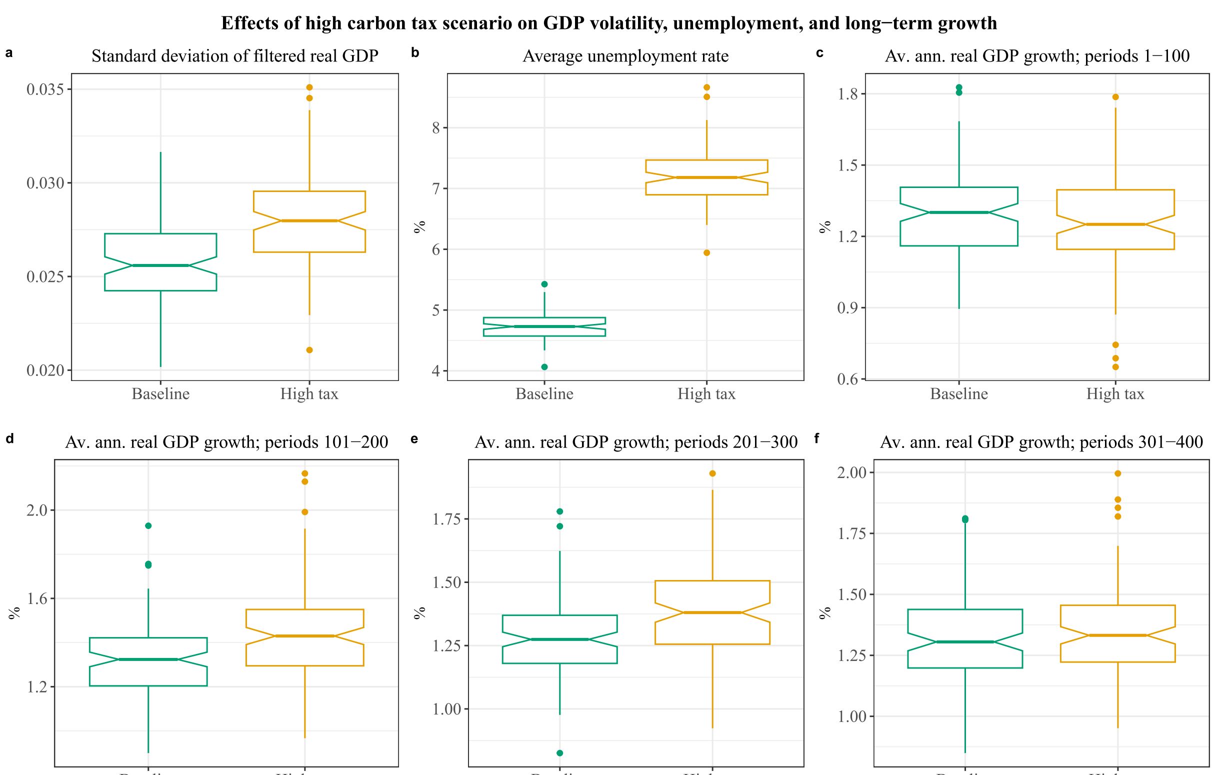

Fig. 6. Panel (a): Standard deviation of filtered simulated quarterly real GDP in the baseline and under a high carbon tax; Panel (b): Average unemployment rate in the baseline and under a high carbon tax; Panels (c) to (f): Average annualised growth rate of simulated real GDP in the baseline and under a high carbon tax. Panel (c): Post-transient simulation periods 1–100; Panel (d): Post-transient simulation periods 101–200; Panel (e): Post-transient simulation periods 201–300; Panel (f): Post-transient simulation periods 301–400. The respective statistics are calculated for each of the 108 individual model evaluations for each scenario, so that boxplots illustrate their distribution in the respective scenarios.

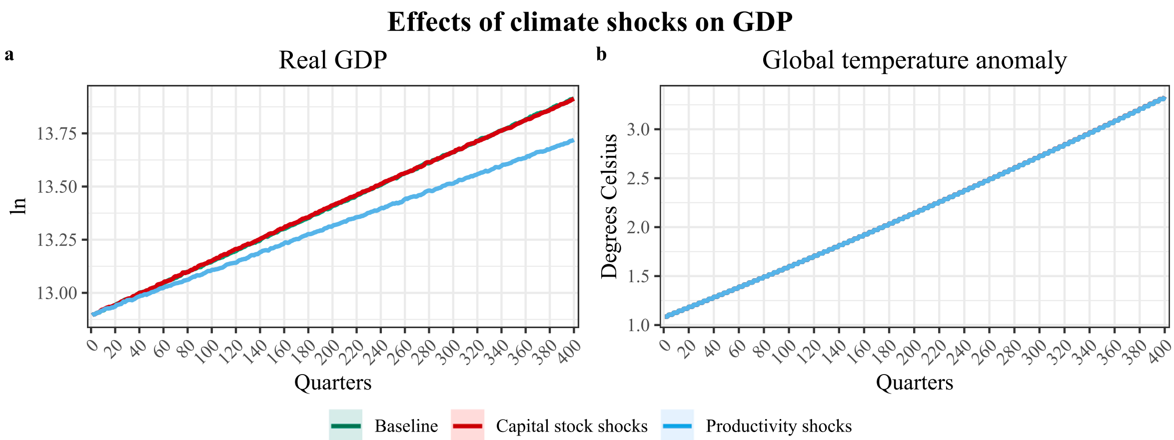

Fig. 7. Panel (a): Natural logarithm of real GDP in the baseline and climate shock scenarios; Panel (b): Global temperature anomaly relative to pre-industrial temperature in the baseline and climate shock scenarios. Bold lines represent averages across 108 simulations with different seeds. Shaded bands represent 95% confidence intervals.

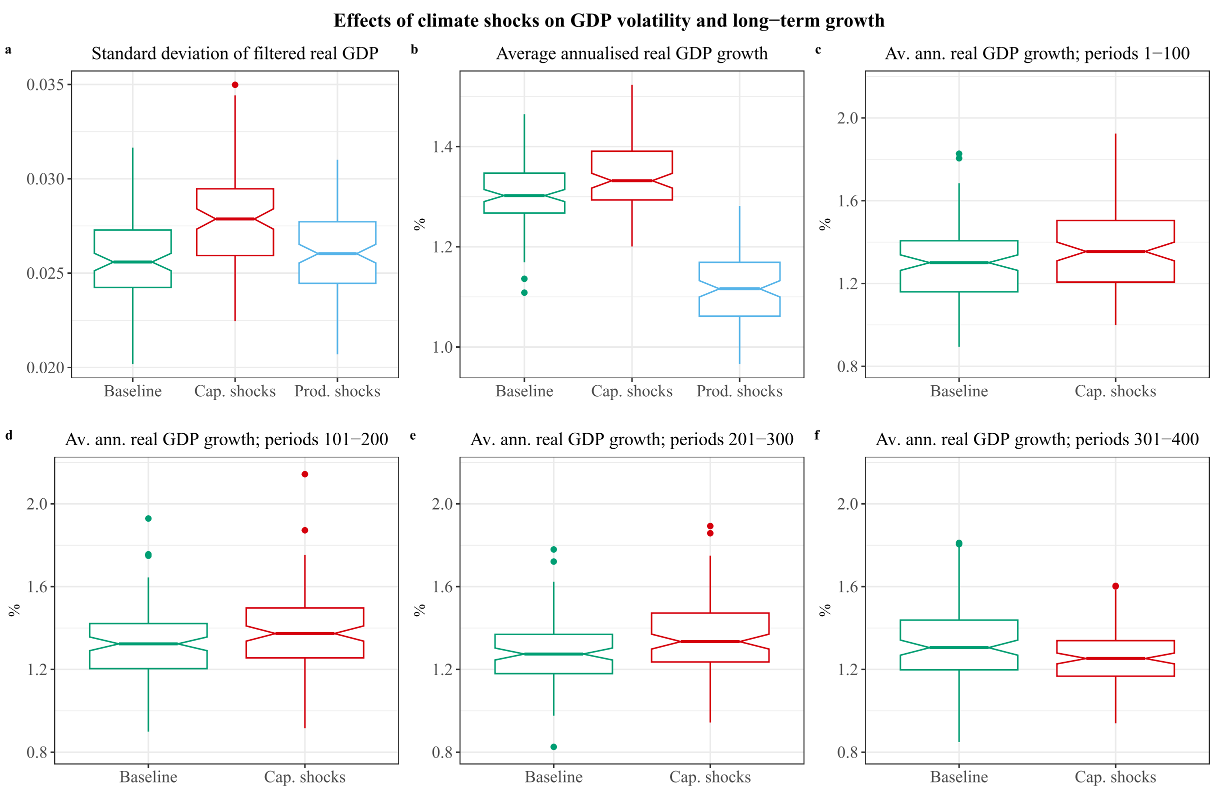

Fig. 8. Panel (a): Standard deviation of filtered simulated quarterly real GDP in the baseline, under shocks to capital stocks, and under shocks to productivity; Panel (b): Average annualised growth rate of simulated real GDP in the baseline, under shocks to capital stocks, and under shocks to productivity; Panels (c) to (f): Average annualised growth rate of simulated real GDP in the baseline and under shocks to capital stocks; Panel (c): Post-transient simulation periods 1–100; Panel (d): Post-transient simulation periods 101–200; Panel (e): Post-transient simulation periods 201–300; Panel (f): Post-transient simulation periods 301–400. The respective statistics are calculated for each of the 108 individual model evaluations for each scenario, so that boxplots illustrate their distribution in the respective scenarios.

average growth is lower than in the baseline. This is in line with results from previous versions of the DSK model (e.g. Lamperti et al., 2019a), which showed that capital stock shocks, as long as they are sufficiently small, can lead to a temporarily positive effect on GDP growth due to efforts to rebuild the lost capital stocks. As the average size of shocks as well as the frequency of extreme events increases with the temperature anomaly, however, negative effects on the rate of growth eventually come to dominate.

Despite their limited impacts on the rate of growth, shocks to capital stocks have important detrimental impacts which arise from the increase in macroeconomic volatility highlighted in Fig. 8. Fig. 9 depicts a number of statistics which further illustrate these impacts, drawing on the model's improved ability to track financial variables thanks to the added SFC structure. Panel a shows that shocks to the capital stock of C-Firms increase the incidence of bank failures. This effect can be explained through two channels. Firstly, the loss of a portion of its capital stock represents a loss to a C-Firm which may push it into bankruptcy, leading it to default on (part of) its outstanding loans. Since the nominal value of capital stocks was previously not taken into account in calculating C-Firm net worth, this represents a novel feedback channel introduced by making the model stock-flow

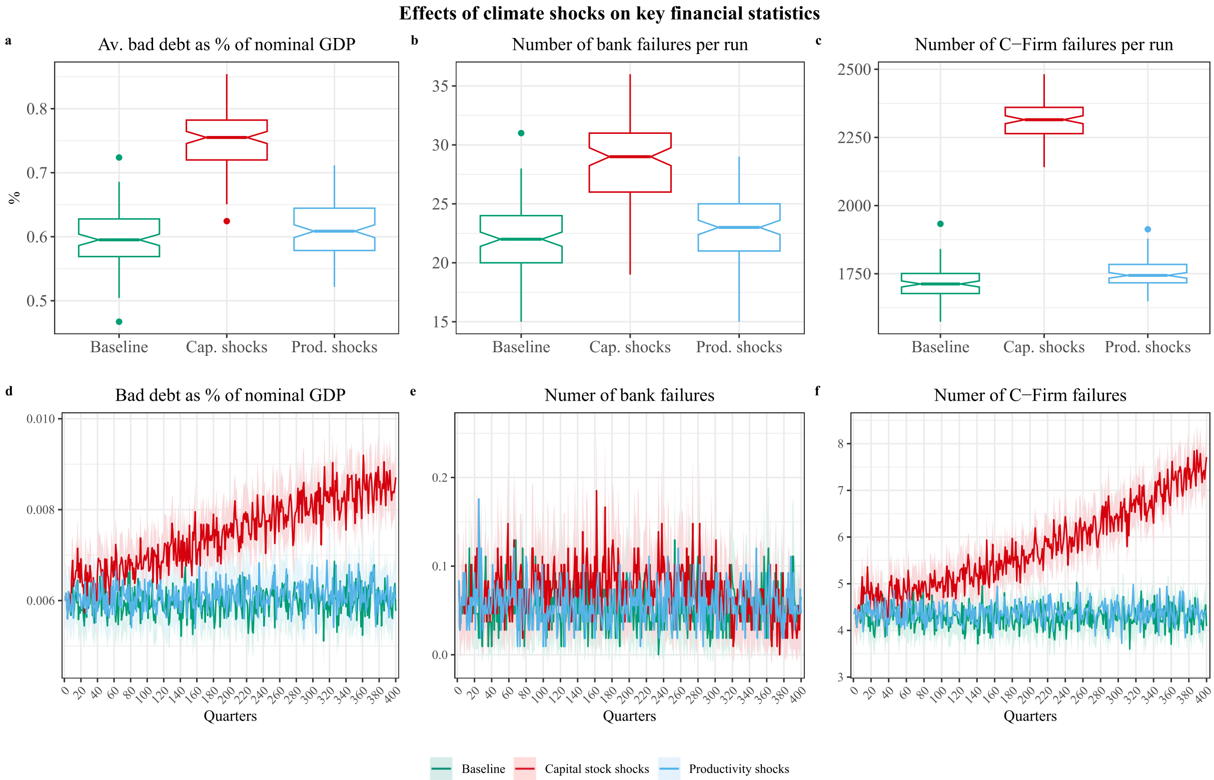

Fig. 9. Panel (a): Average value of defaulting C-Firm debt as percentage of nominal GDP over the post-transient duration of model runs in the baseline, under shocks to capital stocks, and under shocks to productivity; Panel (b): Number of bank failures over the post-transient duration of model runs in the baseline, under shocks to capital stocks, and under shocks to productivity; Panel (c): Number of C-Firm failures over the post-transient duration of model runs in the baseline, under shocks to capital stocks, and under shocks to labour productivity and energy efficiency. The respective statistics are calculated for each of the 108 individual model evaluations for each scenario, so that boxplots illustrate their distribution in the respective scenarios. Panel (d): Time-series of defaulting C-Firm debt as percentage of nominal GDP in the baseline, under shocks to capital stocks, and under shocks to productivity; Panel (e): Time-series of per-period bank failures in the baseline, under shocks to capital stocks, and under shocks to productivity; Panel (f): Time-series of per-period C-Firm failures in the baseline, under shocks to capital stocks, and under shocks to productivity. Bold lines represent averages across 108 simulations with different seeds. Shaded bands represent 95% confidence intervals.

consistent. Secondly, the additional investment which C-Firms undertake to rebuild destroyed capacity must be financed, cet. par. making them more financially fragile. Indeed, Panels b and c of Fig. 9 show that both the number of C-Firm failures per run and the average per-period value of bad debt as a percentage of nominal GDP increase in the presence of capital stock shocks. Shocks to productivity and energy efficiency, by contrast, have only a slight effect on the statistics shown in Fig. 9 since they give rise to initially small, slowly growing impacts rathert than large, sudden distruptions. Panels d to f of Fig. 9 depict time-series for the same statistics shown as boxplots in panels a to c. Panel f shows that under shocks to capital stocks, the average number of C-Firm failures per period increases steadily over time. By contrast, the average number of bank failures under capital stock shocks, shown in panel e, remains elevated for some time but eventually returns to its baseline value, indicating that the bailout mechanism eventually gives rise to an increased degree of robustness to climate shocks in the banking sector. In addition, Panel d indicates that bad debt as a percentage of nominal GDP grows more slowly than the number of firm failures towards the end of the simulation as firms become increasingly unwilling to take on debt to replace lost capital stocks.

The newly added SFC structure also allows for a close examination of the effects of climate shocks on sectoral net worths, which are shown in Fig. 10.

Panel a of Fig. 10 suggests that the main financial burden inflicted by capital stock shocks is ultimately borne by households. This effect stems from the introduction of firm entry financing by households, which was introduced to make the model stock-flow consistent. Under capital stock shocks, households must finance an increasing number of firm re-entries mirroring the rising rate of firm failures, with this financing process also preventing the net worth of C-Firms as a percentage of nominal GDP from declining precipitously despite the presence of shocks to capital stocks. This decline in household wealth naturally also has a negative effect on consumption out of such wealth. The bailout process appears able to keep bank net-worth relatively stable. In contrast to the results shown in Lamperti et al. (2019a), the additional burden from bailout payments on the public budget do not decrease the net worth of the government, suggesting that the bailout costs under a stock-flow consistent tracking of bank net worth are lower than in previous versions of the model. From period 300 the net worth of banks as a percentage of nominal GDP begins to decline. As shown in Panel e of Fig. 9, this interestingly corresponds with a *slowdown* in the rate of bank failures and is mainly driven by a decline in banks' lending business as firms become increasingly unwilling to take on debt to replace destroyed capital items. This relative 'shrinking' of the banking sector is also accompanied by an *improvement* of the public sector's net worth position.

By contrast, Panel b of Fig. 10 suggests that the 'orderly' slowdown in growth induced by productivity shocks does not have large systematic impacts on the financial positions of sectors, with the exception of K-Firms, whose net worth as a share of nominal GDP is persistently negatively affected as a consequence of the slowdown in productivity innovations.

Finally, Fig. 11 shows the impact of the two climate shock scenarios on endogenous emissions. In the case of shocks to the capital stock, losses of installed capital goods lead to an increase in production aiming to replace them, producing slightly higher emissions. While productivity shocks give rise to a very sizeable loss in real GDP, emissions remain

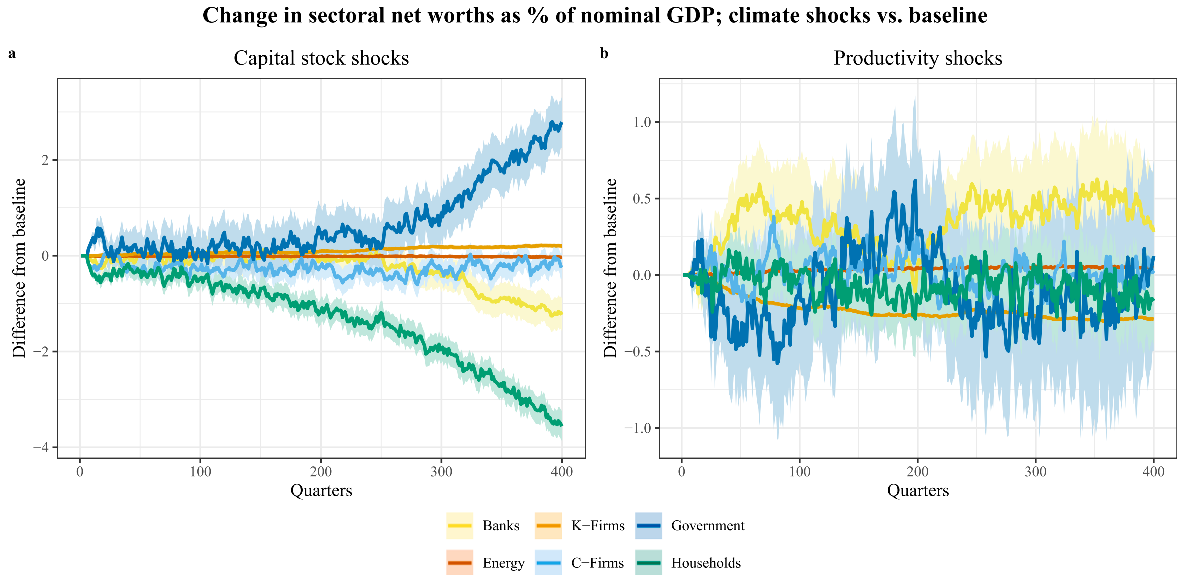

Fig. 10. Sectoral net worths as percentage of nominal GDP, differences between climate shock and baseline scenarios. Bold lines represent averages across 108 simulations with different seeds. Shaded bands represent 95% confidence intervals.

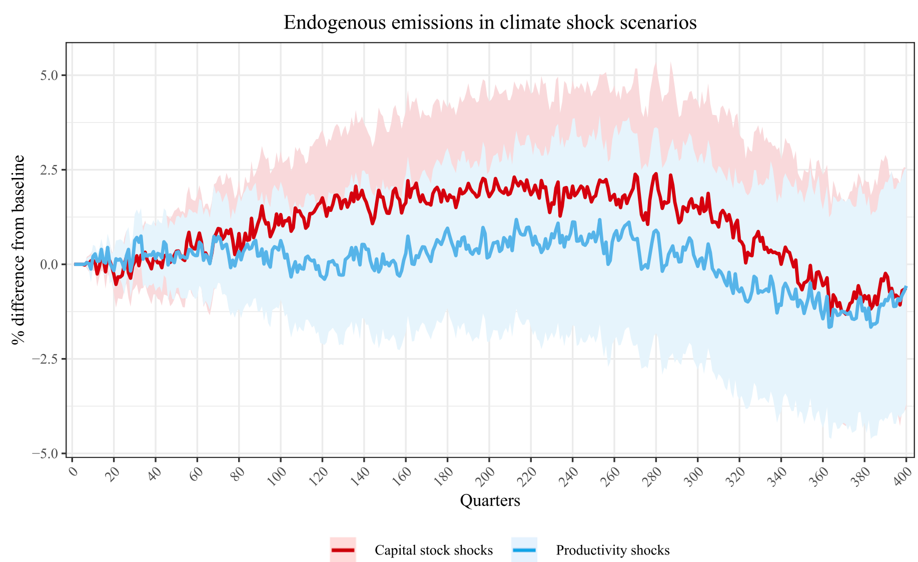

Fig. 11. Endogenous per-period emissions under shocks to capital stocks, and under shocks to productivity, as % difference from the baseline. Bold lines represent averages across 108 simulations with different seeds. Shaded bands represent 95% confidence intervals.

almost constant. Recall that the productivity shocks also affect the energy efficiency of capital goods and K-Firm production techniques. This increases the amount of energy demanded per unit of output and hence prevents a decline in emissions alongside real GDP.

7.3. Unemployment benefits

As a last experiment, we simulate two scenarios in which the unemployment transfer (the payment received by households per unit of unemployed labour as a share of the current nominal wage) is permanently increased. In particular, the baseline value of 0.4 is moved to 0.45 in the first case, and to 0.6 in the second.

Panel a of Fig. 12 shows that in both cases, the increase in benefit payments gives a one-off boost to real GDP, which permanently shifts to a higher trajectory relative to the baseline (without, however, subsequently growing faster), with the boost being larger in the scenario involving a larger increase in the benefit ratio. Importantly, as shown by Panel b of Fig. 12, the increased payments per unit of unemployed labour do not lead to a significant change in the ratio of government debt to nominal GDP. The increase in the benefit ratio hence appears to be self-financing in both cases. While government outlays per unit of unemployed labour are higher, the higher level of real GDP relative to the baseline is accompanied by a decline in the unemployment rate as well as an increase in tax revenue. Despite the change in the consumption function, the model hence appears to still feature a high fiscal multiplier, in line with results from previous versions of the DSK/K+S framework (Dosi et al., 2017a). In addition, it should be noted that the effect of changes in unemployment benefits specifically is partly driven by the assumption of an inelastic labour supply, which is common in both SFC models and macroeconomic ABMs (e.g. Assenza et al., 2015; Dafermos et al., 2017).

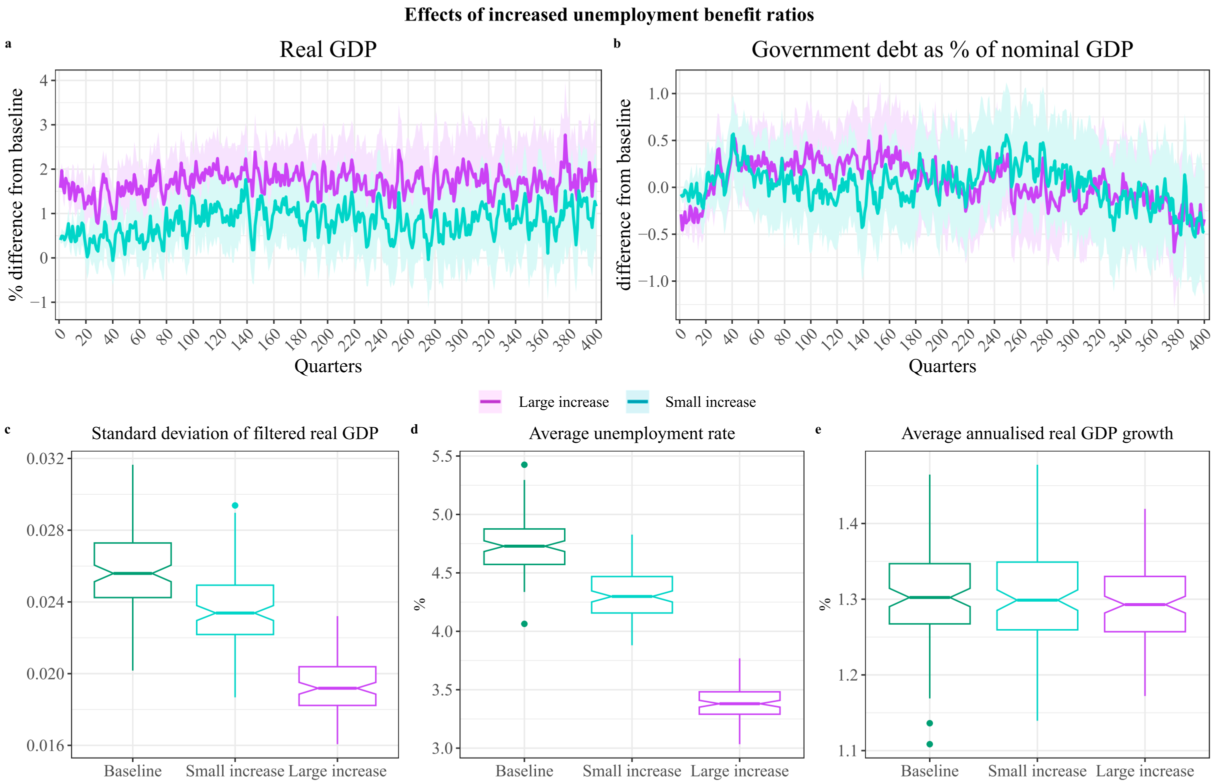

Fig. 12. Panel (a): Real GDP with increased unemployment benefit ratios, as % difference from the baseline; Panel (b): Government debt as percentage of nominal GDP with increased unemployment benefit ratios, difference from the baseline. Bold lines represent averages across 108 simulations with different seeds. Shaded bands represent 95% confidence intervals. Panel (c): Standard deviation of filtered simulated quarterly real GDP in the baseline and under increased unemployment benefit ratios; Panel (d): Average unemployment rate over the post-transient duration of model runs in the baseline and under increased unemployment benefit ratios; Panel (e): Average annualised growth rate of simulated real GDP in the baseline and under increased unemployment benefit ratios. The respective statistics are calculated for each of the 108 individual model evaluations for each scenario, so that boxplots illustrate their distribution in the respective scenarios.

In line with previous results from works using a K+S framework (e.g. Dosi et al., 2010, 2013), Panel c of Fig. 12 suggests that an increase in the benefit ratio also contributes to macroeconomic stability in both scenarios, showing that the standard deviation of filtered real GDP declines significantly in both scenarios. In addition, the higher levels of real GDP in the scenarios also result in lower average unemployment rates, shown in Panel d. Panel e confirms that, as can also be deduced from Panel a, the long-term growth rate of GDP is unaffected by the higher benefit ratios.

8. Conclusions

This paper presented a fully stock-flow consistent version of the 'Dystopian Schumpeter meeting Keynes' (DSK) agent-based integrated assessment model. This is the first integrated assessment model featuring full stock-flow consistency, agent heterogeneity, bottom-up climate impacts and endogenous growth and fluctuations. In this updated version, all balance sheet items and transaction flows are explicitly and consistently tracked throughout a simulation run. This ensures that simulation data correctly and fully capture the implications of simulated scenarios for agent and sector-level balance sheets and financial ratios.

The paper and its appendices also provide the most detailed description of a model from the widely used 'Keynes + Schumpeter'/DSK family (Dosi et al., 2010, 2017b; Dosi and Roventini, 2019) available in the literature to date, hence representing an important reference point for researchers in the sub-field. The paper also gave an outline of key improvements which have been made to the model code to ensure accessibility and usability. Following a description of the calibration and validation process, a range of example scenarios were presented, showing that the model can be used to address a variety of research questions related to macroeconomic and climate policy, as well as the economic impacts of climate change. We showed that carbon taxation, while being reasonably successful at curbing emissions, may also entail a significant macroeconomic cost. Investigating the economic impacts of climate shocks, we found that the effects depend strongly on the channel, with shocks to productivity slowing the growth rate of the economy and shocks to the capital stock chiefly affecting macroeconomic volatility and financial stability. Finally, we showed that the model can also be used for non-climate-related macroeconomic policy experiments by demonstrating the stabilising effect of an increase in unemployment benefits.

The new fully specified accounting framework of the model lays an important foundation for planned future extensions. Some major simplifications of the present version include the assumption of a fully static bank-customer network, the modelling of bank loans as credit lines which must be rolled over in every period, the absence of lending to the energy sector, and the modelling of the household sector as an aggregate entity. The former three constrain the analysis of the financial stability implications of climate change and climate policy and will be addressed in already ongoing work. The fourth precludes analyses of the consequences for personal income and wealth distribution, which may result both from climate change impacts and climate policy. As considerations of just transitions grow in importance (Galanis et al., 2025), an extension of the DSK-framework along this dimension would appear reasonable.

The stock-flow consistent accounting framework now underlying the model will greatly ease the implementation of a dynamic credit network and multi-period loans, as well as the linking of an agent-based household sector to the financial system and the rest of the economy. Finally, the energy sector is simplified in many respects. A more detailed modelling of the energy sector, including a wider variety of green and brown technologies, its investment behaviour and the financial implications thereof, will be a priority in future extensions of the framework.

CRediT authorship contribution statement

Severin Reissl: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Luca E. Fierro:** Writing – original draft, Software, Methodology, Conceptualization. **Francesco Lamperti:** Writing – review & editing, Methodology, Conceptualization. **Andrea Roventini:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ecolecon.2025.108641.

Data availability

The model code, including the input files used for the simulations shown in the present work, are available at https://doi.org/10.5281/zenodo.15231126.

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