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ESD Ideas: Reliable Adaptation Policies to Sea-Level Rise Require Incorporating Complexity in Economic Models

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Abstract. With trillions of USD in assets facing climate-induced sea-level rise, oversimplified economic models might misinform responses. By capturing non-linearities in interconnected socio-economic and biogeophysical domains, and their local to global co-evolution, complexity science applied to sea-level rise uniquely enhances adaptation policies.

Main text.

Coastal regions urgently need to identify cost-effective solutions to adapt to ongoing sea-level rise (SLR). Given massive coastal urbanisation, these decisions involve hundreds of billions of USD per year in adaptation costs to protect trillions in asset values and about a billion people (Intergovernmental Panel on Climate Change, 2022). Potential damages ramping up to as much as 10% of the global GDP by 2100 could be avoided with coastal adaptation (Intergovernmental Panel on Climate Change, 2022). Because of the committed SLR due to climate system inertia, including the risk of ice-sheet disintegration, adaptation strategies are vital even if climate change would stabilise at 1.5 or 2 degrees above pre-industrial temperatures. Despite this grand challenge, substantial gaps remain in modelling coupled coastal biogeophysical and socio-economic dynamics.

Economics, coupled with other social and natural sciences, can and should inform about the consequences of climate change and guide the allocation of limited resources for development and adaptation. Yet, existing economic approaches to analysis and modelling of SLR economics present several key limitations, in particular for what concerns (i) agents' bounded rationality, learning, risk perception and behavioural responses, including adaptation actions as a feedback to impacting events, (ii) inequality and distributional impacts, (iii) indirect socio-economic losses and their relationship with direct damages, (iv) adaptation processes over time, often causing over-optimistic assumptions on their proactiveness and effectiveness, and ignoring long-term (multi-century) adaptation needs, (v) trade-offs and co-benefits across time and space, e.g. coastal protection exporting risk to adjacent areas, (vi) interlinkages between planned and autonomous adaptation, and (vii) global scenarios considering systemic financial and geopolitical risks.

In particular, current economic approaches supporting adaptation policies usually adopt a disconnected combination of cost-benefit analyses (CBA) focusing on local and regional contexts, and macroeconomic models (mostly Computable General Equilibrium models, CGE) exploring future scenarios at global or national scales. CBA in the SLR context typically focuses on expected values of costs and benefits at one or two time horizons. By presenting aggregated results they omit the tail risk

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and the effect of extreme events, which are very relevant especially at the level of local communities (Jafino et al., 2021). When applied to SLR, aggregation in CBA ignores dynamic interactions, e.g. with adaptive policies, and often masks inequality issues between different regions, actors and generations.

Most CGE used in the SLR and adaptation literature have coarse spatial resolution and omit economic, social and financial processes characterised by complex dynamics (Kompas et al., 2018). Several CGE features can lead to substantial underestimation of SLR damages and losses. First, assumptions on linearity of damages, and averaging over large geographical areas in deterministic impact assessments, by construction rule out the tail risk that emerges from nonlinear dynamics and spatio-temporal variabilities. In addition, the heterogeneity of adaptation capabilities across communities and the potential failure of adaptation measures can also lead to tail risk. Second, CGE typically ignores responses of complex adaptive economic systems to formidable risks (Van Ginkel et al., 2022), and has limited capabilities to treat non-marginal changes, i.e. climate tipping points; (Dittrich et al., 2016). Third, most local studies ignore indirect damages, and macroeconomic assessments only quantify them at an aggregated level, i.e. the national scale. In contrast, estimates of indirect damages of SLR based on granular asset-level data can be an order of magnitude higher for some regions, even without consideration of climate tipping points (Cortés Arbués et al., 2024). Yet, when assessments of direct and indirect macroeconomic costs omit coastal adaptation, they overestimate the 21st century SLR damages by orders of magnitude (Hinkel et al., 2021).

Here we present solutions for enhancing models of the economics of SLR, accompanied with visuals reflecting our opinion (Fig. 1). A key overarching challenge is to assess better the connection between macro-level models – capturing investment responses across sectors – and micro-level models. Complex systems methods are particularly useful for capturing the nonlinearities emerging from multi-scale dynamics that are needed to improve SLR economic assessments. Adaptation actions and shifts in vulnerability actively reshape the complex networks of socio-economic interactions, which in turn constrain and influence their dynamics.

Behaviours of out-of-equilibrium complex systems with boundedly-rational agents in space can be explored with agent-based models (ABM) linking the individual to regional, national and global scales. ABM can specifically improve the local representation of diverse adaptation constraints, and the distributional impacts of both climate-induced hazards and adaptation actions, thus improving SLR assessments beyond the results of CBA (cf. Taberna et al., 2023). ABM can also assess whether such complex nonlinear dynamics could lead to a socio-economic tipping point of regional or national magnitude (e.g. van Ginkel et al., 2022).

Remarkably, ABM with stock-flow consistent macro-scale depictions of finance-economy feedback loops can capture the effects of large-scale floods on credit risk positions of banks and other financial institutions that have assets concentrated in hazardous areas (see e.g. Dunz et al., 2023). Capturing such cross-scale dynamics can overcome the limitations of CGE and

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substantially enhance SLR assessments, by enabling key insights linking spatial, fiscal and financial decision-making. Complex network analysis can also be regarded as filling the crucial micro to macro gap (e.g. Verschuur et al., 2023); networks can include research on individuals' behaviour.

Linking process-based probabilistic biophysical coastal models (e.g. Ranasinghe, 2020) in a highly disaggregated and spatially-explicit way with simulations of complex social dynamics that non-linearly amplify vulnerability would particularly enhance socio-economic equity assessments of SLR (cf. Jafino et al., 2021). These approaches can also be combined with dynamic adaptive policy pathways to assess the interaction between autonomous and planned adaptation. In doing so, it is crucial to consider the dynamic nature of coastal adaptation and the influence of potential future learning about SLR. Learning implies the need to assess the costs of switching adaptation pathways, while planning for a range of futures (e.g. Völz et al., 2024; Haasnoot et al., 2020).

Capturing interconnected nonlinear dynamics across domains and scales will improve assessments by mitigating issues of risk underestimation and maladaptation (which might lead to costly lock-ins and actions that exacerbate inequalities) while facilitating reliable decision-making from the near to long term.

Figures.

Figure 1: Panel (A) presents a Sankey diagram with links between the main issues (left) and their corresponding solutions (right) on how to improve practice on modelling the economics of sea-level rise. The panel shows that some issues are highly connected, linking with numerous solutions and indicating greater complexity. Notably, "scaling and multi-scale interactions", "model validity, credibility, legitimacy and realism", and "complex dynamic modelling", are interconnected with a high number of potential solutions. These issues could be addressed through various solutions, including "network analysis" and "dynamic adaptive pathways". Then two separate networks presents the interrelations within (B, left) issues and (C, right) solutions in. In these networks, a link between two issues represents the number of solutions they share, and, conversely, a link between two solutions represents the number of issues they have in common. The size of nodes indicates the centrality of each item in the network, and the colours of the nodes signal the membership to communities of strongly interlinked items. In (a) two distinct communities of issues appear more densely interconnected. In the largest community, the node representing "model validity, credibility, legitimacy, and realism" is highly connected. This community also reflects an interest in "complex dynamic modelling" and "multi-scale interactions". This aligns with the growing relevance of complex multi-hazard risks, and with literature showcasing new solutions for compound risks (e.g. Schlumberger et al., 2024) and multi-scale modelling. Compound risks could lead to cross-scale cascades of damages and to major losses of socio-economic resilience. In relation to the smallest community in (a), this underscores the need for stronger "model integration". In (b) the largest of three communities presents strong interrelationships involving system dynamics, agent-based, and multi-scale (local to global) models i.a., integrating techniques to address nonlinearities and non-equilibrium phenomena, ultimately enhancing decision-support tools involving cost-benefit or multi-criteria analyses. The second community comprises methodological approaches that are considered to have a great potential for SLR economics, like network analysis (e.g. Verschuur et al., 2023). Last but not least, another community encompasses solutions associating adaptation to finance, insurance and behavioural research.

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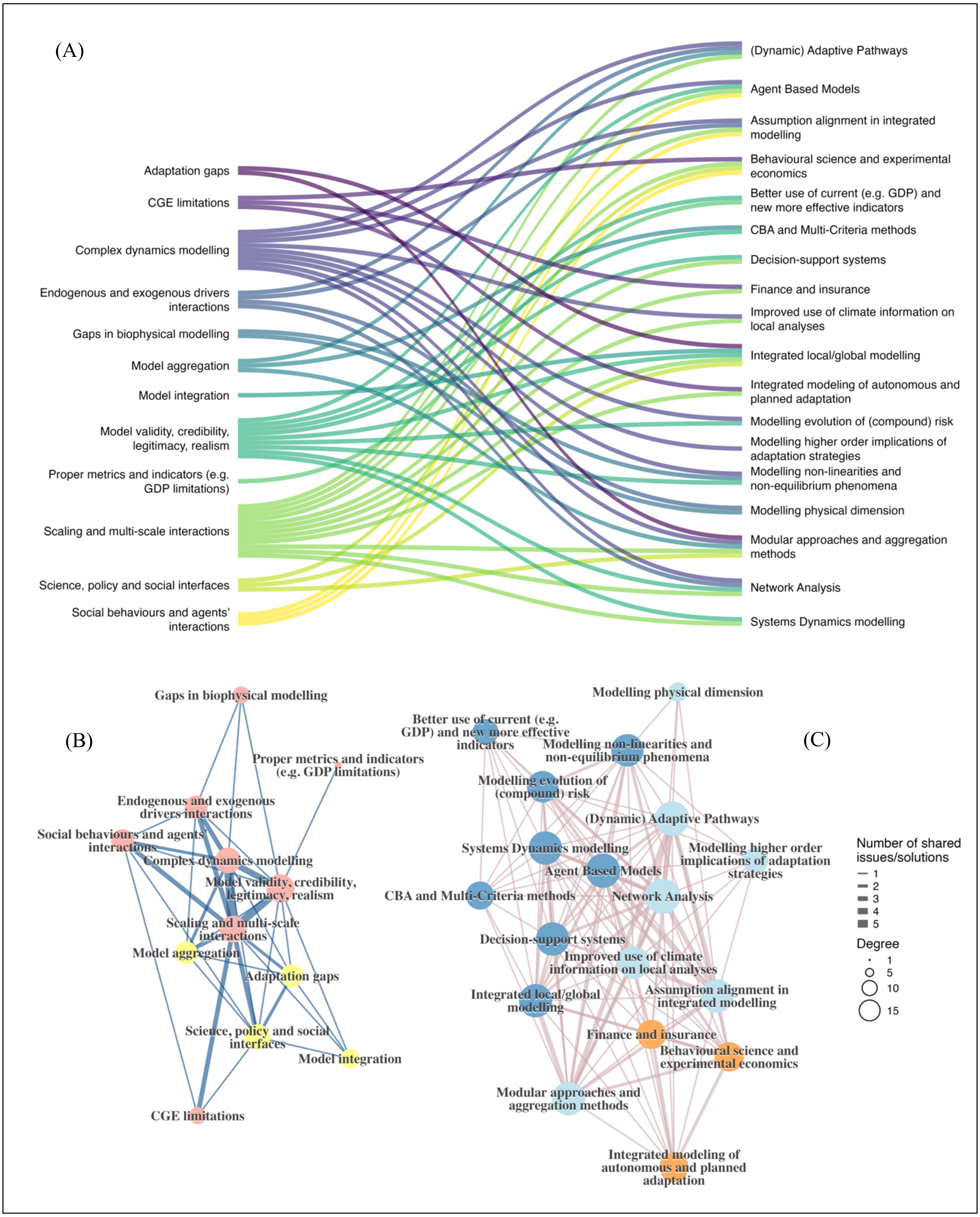

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Author contributions

C.G. and R.C. conceptualised and coordinated the manuscript. R.C. and S.R. prepared the original manuscript. S.R. created the figure. R.C., C.G., S.R., S.B., F.B., T.F., M.H., S.H., J.H., P.L., A.M., I.M., R.N., A.V., K.v.G., and V.V. contributed to the final version of the manuscript. All authors critically reviewed, commented, and carefully revised the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Review statement

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