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Uncertainty in boundedly rational household adaptation to environmental shocks

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Despite the growing calls to integrate realistic human behavior in sustainability science models, the representative rational agent prevails. This is especially problematic for climate change adaptation that relies on actions at various scales: from governments to individuals. Empirical evidence on individual adaptation to climate-induced hazards reveals diverse behavioral and social factors affecting economic considerations. Yet, implications of replacing the rational optimizer by realistic human behavior in nature–society systems models are poorly understood. Using an innovative evolutionary economic agent-based model we explore different framings regarding household adaptation behavior to floods, leveraging on behavioral data from a household survey in Miami, USA. We find that a representative rational agent significantly overestimates household adaptation diffusion and underestimates damages compared to boundedly rational behavior revealed from our survey. This "adaptation deficit" exhibited by a population of empirically informed agents is explained primarily by diverse "soft" adaptation constraints—awareness, social influences—rather than heterogeneity in financial constraints. Besides initial inequality disproportionally impacting low/medium adaptive capacity households post-flood, our findings suggest that even under a nearly complete adaptation diffusion, adaptation benefits are uneven, with late or less-efficient actions locking households to a path of higher damages, further exacerbating inequalities. Our exploratory modeling reveals that behavioral assumptions shape the uncertainty of physical factors, like exposure and objective effectiveness of flood-proofing measures, traditionally considered crucial in risk assessments. This unique combination of methods facilitates the assessment of cumulative and distributional effects of boundedly rational behavior essential for designing tailored climate adaptation policies, and for equitable sustainability transitions in general.

agent-based model | exploratory modeling | survey | climate change adaptation | distributional impacts

Contending with the impacts of climate change demands engagement from all levels of society (1). Central to dealing with these impacts is the apprehension of how effectively and timely various actors adapt. To this end, simulation models are critical to quantify effects of adaptation strategies. Large-scale government-led measures to curtail climate change adversities typically rely on aggregated data and are regularly incorporated into models as rational decisions, either based on cost-benefit analysis (2) or as adaptive policy pathways accounting for uncertainty (3). Due to the simplicity of assumptions and the relative data availability, climate change adaptation (CCA) modeling predominantly focuses on government-led decisions (4).

Accounting for private actions is a key priority for CCA (5). Household adaptation complements government-led actions, has the potential to dynamically respond to the accelerating climate-induced adversities, and is essential in multiscale CCA (6). Yet, the lack of microdata on individual behavior and the uncertainty which its inclusion begets in simulation models has engendered that households' actions are widely omitted from CCA models. Modeling human behavior is also a fundamental challenge in climate risk assessments (7–9) and the broader sustainability science, where balancing socio-economic priorities alongside interactions with the environment in dynamic nature–society systems is essential (10, 11).

Among the sustainability models that do consider human behavior, many assume rational representative households with perfect information who make optimal choices driven by financial constrains (12). However, across various nature–society systems, empirical work consistently demonstrates that human behavior deviates from a perfectly rational optimizer (13). For instance, in CCA, households rely on heuristics such as affect (worry), social pressure, and perceived coping capacity (14, 15). Diversity in education,

Significance

Understanding household behavior and its macro consequences for society is pivotal for climate change adaptation. Yet, traditional policy decision-support models for nature–society systems oversimplify human behavior. Using original modeling and survey data, we assess uncertainty in adaptation diffusion and in damages along a gradient of assumptions about behavior. We show that adaptation is below economically optimal, largely due to diverse adaptation constraints (awareness, self-efficacy, social norms) rather than heterogeneous financial constraints. By modeling behavior change shaped by social institutions—descriptive norms and markets—we trace mechanisms affecting inequality dynamics. Our results demonstrate that behavioral uncertainty can mediate the importance of physical factors traditionally thought to be decisive for the uptake of adaptation measures, calling for a tailored policy design.

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incomes, experiences, and institutions endow individuals and societies with diverse adaptive capacities (16). Real CCA uptake is below what would be economically efficient (5, 17), suggesting that households do not act as homo-economicus when adapting to environmental shocks and that diverse adaptation constraints shape soft limits to adaptation (18). The gap between CCA as estimated by a perfectly rational decision maker and reality produces an unaccounted "adaptation deficit"—insufficient (public or private) adaptation compared to what is economically optimal. The fundamental challenge for sustainability science, and for CCA in particular, remains: means to represent empirically rich human behavior in formal models and to quantify aggregated and distributional impacts of private actions are in paucity.

Agent-based models (ABMs) are designed to simulate boundedly rational behavior of many heterogeneous actors who interact with each other and their environment and continuously learn (19, 20). ABMs rely on social science theories and data to define rules of action, interactions, and learning that drive behavioral change and evolution of institutions (21, 22). With respect to climate-induced hazards, ABMs increasingly examine the cumulative consequences of household adaptation, including ramifications in damages and recovery from climate-induced hazards. However, current models still face several limitations, including the lack of microdata on human behavior, derivation of distributional impacts, and lack of modeling households' interactions with firms that offer jobs and endogenously define incomes crucial for adaptive capacity and individual as well as regional socio-economic resilience (8, 9). Here, we employ behavioral survey data in an evolutionary economic ABM (23), endowed with firms and households that interact through socio-economic institutions (markets and social networks) to quantitatively explore the spectrum of household adaptation behavior to the most costly climate-induced hazard: floods. With urbanization exasperating the growing risk brought on by floods and sea level rise, we focus our model on emulating an urbanized coastal region and populate it using behavioral data from surveys conducted in Miami-Dade county, USA, in 2020 (14). Using empirical data on flood probabilities and capital/labor ratios of the regional economy, we contrast how various behavior representations (homogeneous vs. heterogeneous; rational vs. empirically informed boundedly rational) impact the CCA diffusion, and the distribution of damages. In the behaviorally-rich framing, the diverse boundedly rational agents in our model are embedded into a social network, where they learn from peers and are influenced by evolving social norms. Households are also endowed with education, individual awareness about hazards (perceived damages, worry about floods), past experience with floods and undergone adaptations—significantly extending the typical financial constraints to adaptation that a rational optimizer faces. Finally, our introduction of a full macroeconomic framework—where households interact with firms—enables tracing endogenous changes in households' incomes and indirect flood consequences, like firms' bankruptcy leading to unemployment, which undermines households' recovery and widens inequalities. These alternative representations of household adaptation, embedded in a large socio-economic system and exposed to environmental shocks, reflect the inherent epistemic challenges in representing human behavior in sustainability science models in general.

Recognizing these deep uncertainties, we employ exploratory modeling (24) to study alternative modeling assumptions, including rival framing of behavioral representation and uncertainties in key physical factors shaping risks. Exploratory modeling is uniquely appropriate for contending with the diversity of human behavior in complex nature–society systems (24, 25). By combining the economic ABM with survey data on CCA behavior and exploratory modeling, we examine how uncertainty in the representation of human behavior interacts with physical uncertainties to affect the diffusion of private adaptation, to shape overall regional damages, their distribution, and the corresponding recovery pathways of different households. In systematically analyzing behavioral uncertainty stemming from the various formulations of household adaptation decisions, we tackle three research questions: 1) How does heterogeneity in financial constraints and socio-behavioral factors affect regional patterns of adaptation diffusion? 2) What are the distributional and indirect economic impacts of hazards and of behavioral change among households with different adaptive capacities? 3) Does physical uncertainty, like exposure and objective effectiveness of measures—factors conventionally crucial for CCA policy design—remain predictable across alternative behavior framings?

Integrating various decision-making processes ranging from a representative Rational Agent (*RA*) to a heterogeneous population of Boundedly rational Agents (*BA*), our model traces the collective consequences of household behavior and maps emerging equity implications across agents with various adaptive capacities. *RA* decides to implement a CCA measure when it becomes economically efficient considering only financial adaptation constraints (Fig. 1*B*). Instead, adaptation decisions of *BA* are shaped by diverse adaptation constraints (18): perceptions of worry about floods, of own ability to implement a measure (self-efficacy), past experiences, and social influences, all elicited from the household survey (14). By going beyond the rational representative agent, we trace how heterogeneity and socio-behavioral factors, embedded in evolving social and market institutions, lead to the emergence of adaptation deficits, hence quantifying soft adaptation limits which are otherwise challenging to estimate (5, 17). Using state-of-the-art exploratory modeling, we analyze the behavioral and physical uncertainty jointly, estimating how alternative representations of human behavior in computational models interact with changing physical factors, like hazard exposure. This original combination of methods showcases how simulations and social sciences can be bridged to integrate human behavior in formal models and to quantify socio-economic and equity implications in the next generation of sustainability science models.

Computing Socio-economic Dynamics in Adaptation to Environmental Shocks

Complex Evolving Economy. We embed computational modeling of human behavior into an evolutionary Climate-economy Regional Agent-Based (CRAB) model (23). The model features a complex evolving economy populated by heterogeneous households and firms of three different economic sectors (Fig. 1*A*). Firms invest in R&D to discover newer and more productive technologies that trigger endogenous economic growth, following the Keynes & Schumpeter ("K +S") evolutionary economics tradition (26, 27). Firms compete in capital, labor, goods, and service markets, which are imperfect and characterized by limited information; hence, firms form expectations and update them as they learn. These four market institutions and the technological advancement of firms drive the core economic dynamics—including changes in productivity, GDP, unemployment, households' incomes, and savings—that endogenously define the economic attractiveness of the region and in/out-migration of population and firms (*Materials and Methods* and *SI Appendix*, *Methods*). Households buy goods and services, work in these sectors, and may switch jobs depending on dynamic wages

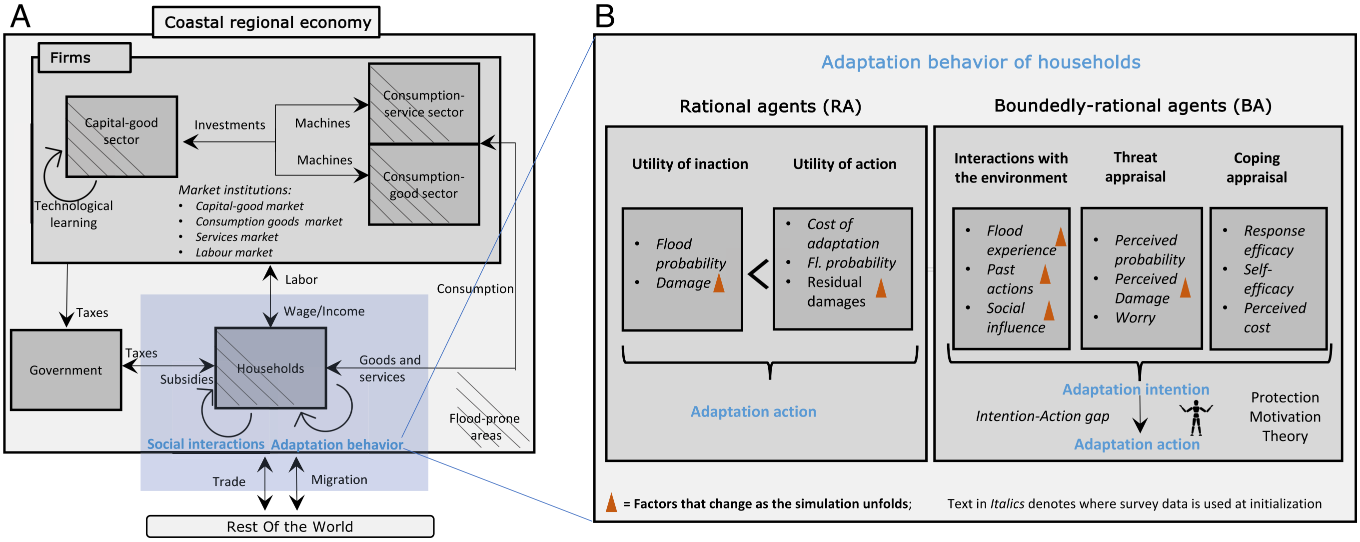

Fig. 1. Evolutionary agent-based model of a regional economy (*A*) with heterogeneous adaptive agents prone to social interactions and behavioral factors (*B*).

or create new firms themselves. The addition of firms interacting with households via market institutions (Fig. 1*A*) is important for quantifying whether unemployment and macroeconomic restructuring in the aftermath of a flood undermines households' recovery, decreases incomes and potentially results in out-migration ultimately affecting the development of the regional economy.

Households and firms can be located in safe or hazard-prone areas. Agents in the hazard-prone area can be impacted by floods, which damage the firms' assets and inventories as well as household assets and productivity. Here, we use a single-region version of the CRAB model (23) to evaluate the role of different behavioral assumptions on household adaptation diffusion and damages in the region. Besides expanding the original model with the service sector and contextualizing it with the aggregated economic and flood data from the greater Miami region (FL, USA), we substantially advance household behavior modeling (Fig. 1*B*). For the latter, we rely on our survey data from Florida (14) eliciting behavioral and social factors of household CCA. To adapt to adversities, households consider three types of structural measures: Wet-proofing, Dry-proofing, and Elevation (28). Elevation is costly but provides complete flood protection. Conversely, the other two measures entail lower costs but with lower objective effectiveness for damage reduction (*Materials and Methods*). Notably, households in our ABM are embedded in a social network where they exchange information about adaptation with their peers, leading to evolving descriptive norms. We initialize our ABM with a synthetic population of $n = 3{,}000$ households (∼5:1000 of Miami-Dade County) and 250 firms (split among the capital-good, service, and consumption-good sectors as 50:100:100), with 40% of these agents randomly allocated to flood-prone areas (*Materials and Methods*).

Household CCA. To model household adaptation, we implement diverse behavioral strategies. As the most widespread representation of human behavior, we first study the dynamics of our regional economy assuming all households are rational agents prone only to financial adaptation constraints. Specifically, *RA* goes through a pure economic assessment of risks by weighing probabilities and damages against the costs of the three adaptation measures (Wet-proofing, Dry-proofing, and Elevation), and adopt them when it is economically efficient (Fig. 1*B*). As the next common step to enrich human behavior in sustainability models, we replace a homogeneous rational agent (RA_{Hom}) by a population of individuals heterogeneous in incomes and damages, yet still rational in their decision-making (RA_{Het}), including their objective perception of probability. We parameterize incomes, probabilities, and damages of RA_{Hom} households with the survey means (*SI Appendix, Model Calibration*), and RA_{Het} with the distributions of the reported survey values.

Yet, ample empirical evidence demonstrates that probabilities and damages used to calculate economic efficiency, alone have little effect on people's intentions to adapt to floods (29). Instead, we ground *BA* agents in the most prominent social science theory explaining CCA behavior: Protection Motivation Theory (PMT) (30, 31). Extended PMT assumes that besides perceived damages and probability, psychological factors—affect heuristics (worry), perceived effectiveness of a measure and of own ability to implement it (response- and self-efficacy), social expectations and past experiences with floods and CCA—drive private adaptation. These socio-behavioral factors either hinder or amplify the household adaptation intentions, and serve as diverse adaptation constraints making individual judgements boundedly rational. The behavior of *BA* agents explicitly captures mechanisms specified by PMT (Fig. 1*B*), and contextualizes them by relying on the survey data (14) (2020 Florida subsample, $N = 965$). To differentiate between three common CCA measures (28)—Wet-proofing, Dry-proofing, and Elevation—we run three theory-grounded logistic regressions (*SI Appendix, Model Calibration*). Notably, PMT specifies mechanisms, via which socio-behavioural factors cause behavioral intention and eventually CCA action, and which proved valid worldwide (15). Hence, the behaviorally-rich adaptation in CRAB and the derived insights are generalizable. Similarly to *RA*, we model the population of boundedly rational households as either homogeneous (BA_{Hom}) or heterogeneous (BA_{Het}).

Additionally, in the *BA* scenarios, households are embedded in a random social network (32), calibrated with our survey data (*SI Appendix, Model Calibration*). When considering a specific CCA, households interact with other agents in their "Social network" and observe which peers have implemented the measure as the simulation unfolds. As *BA* households observe changes in the descriptive norms in their networks, they also update individual CCA intentions. *BA* households learn over time based on the opinions of others (e.g., perceived social expectations regarding own action on adaptation) and own experiences (e.g., perceived damages after a flood). Importantly, while the simulated mechanisms of behavioral change grounded in PMT persist, the initial data-driven effects of socio-behavioral factors evolve individually for each agent (denoted with triangles, Fig. 1*B*) based on the actions of others and their own.

Exploring Behavioral Uncertainty. Besides the baseline scenario without private adaptation, we quantify differences in macro-outcomes along a gradient of rival framing of human behavior: RA_{Hom}, RA_{Het}, BA_{Hom}, and BA_{Het}. Hence, we gradually increase the richness of behavior—moving systematically from a representative rational agent to diverse empirically informed agents with boundedly rational behavior affected by social interactions. We compare these rival assumptions about behavior along macro-metrics (adaptation deficit and damages, *SI Appendix*), each estimated across 100 Monte Carlo runs. By default, CRAB also traces regional GDP, unemployment, net savings, and population of households and firms (23). With respect to shocks, we trace the overall performance of the regional economy and the distributional impacts assuming a scenario with no floods vs. two consecutive floods (occurring at time steps 100 and 140 of the simulation).

We broaden the scope of traditional ABM sensitivity analysis by applying exploratory modeling (24) to diagnose how key conventional drivers of risk interact with alternative behavioral heuristics. Exploratory modeling constructs large ensembles of computational experiments to systematically explore the implications of alternative assumptions. The goal is to elicit interaction mechanisms and to identify uncertainties critical in achieving/avoiding system states of interest (33). Given the complexity of CRAB combined with the effects of structural behavioral uncertainty (agent homogeneity vs. heterogeneity and behavioral heuristics), we focus our parametric diagnostic assessment on the core physical factors affecting households' adaptation behavior: the fraction of population exposed to floods and the objective effectiveness of the three adaptation measures. Uncertainty in these factors stems from several sources. Past data on flood exposure are increasingly uncertain, with climate change exacerbating extreme events, and urbanization affecting hydrological processes. The objective effectiveness of adaptation measures is also highly uncertain due to the scarcity of fragmented empirical data on the actual damage reduction of various adaptations (28). Our exploratory methodology systematically examines how uncertainties in these four factors shape adaptation outcomes under alternative behavioral framing, by applying global sensitivity analysis (SA) to 460,800 computational runs of the CRAB model, as described below.

SA is a widespread class of model diagnostics methods (34, 35). Longitudinal SA, which assesses the importance of uncertain factors over time, is especially pertinent in complex systems (36–38), as it enables the exploration of the path dependence of critical outcomes, or regime-changing conditions, i.e., tipping points. Our model, as other complex systems models simulating many diverse actors and consequential outcomes, has a large number of varying parameters (fraction of exposed households, measures' effectiveness) and delivers multidimensional outputs (fraction of adapted households, household damages, regional or differentiated per level of adaptive capacity). Since they can be variably consequential for different stakeholders, we perform the global SA across all potentially relevant outputs.

Model Verification and Validation. Following the standard practice in ABM development, we perform both micro- and macro-validation (39). Whenever possible, we define the agents' micro rules to match the behavioral patterns in the survey data. Where empirical data are unavailable, we indirectly validate CRAB against relevant micro and macro stylized facts (*SI Appendix, Model Calibration*), as common in the literature (39). The CRAB model successfully reproduces 15 empirical stylized facts characterising regional economic development (23), such as that the floods decrease the entry of firms, their output, and employment opportunities (*SI Appendix, Model Validation*).

Results

Behavioral Biases Rather than Differences in Incomes Impede Adaptation and Increase Regional Residual Damages. A representative rational agent pursues adaptation when it becomes economically efficient. This engenders that thousands of identical optimizing households immediately adopt Wet- and Dry-proofing adaptations (RA_{Hom} in Fig. 2 *A* and *B*) as they are affordable from the start given the reported incomes and savings in our survey. Elevation is adopted gradually (Fig. 2*C*), as RA_{Hom} households need to accumulate sufficient savings to afford it. Hence, the top solid curves in Fig. 2 *A*–*C* signal the optimal level of private adaptation in this regional coastal economy. Introducing heterogeneity in factors shaping financial adaptation constraints—incomes, education, and damages—reduces private adaptation diffusion across all three measures (dotted curves for RA_{Het} adaptation diffusion, Fig. 2 *A*–*C*). This adaptation deficit is just 3–4% for Dry- and Wet-proofing at the end of the simulation (pink area, Fig. 2 *A* and *B*), signaling that diversity among household financial adaptation constraints barely matters for these decisions. This insight is essential since introducing income heterogeneity is the focus of contemporary CCA modeling (7, 8, 40) as an advancement over *RA* in representing human decisions. The ability of CRAB to differentiate between types of CCA in a population with diverse incomes permits to disentangle for which CCA measures heterogeneity in financial adaptation constraints is irrelevant, and for which it matters. For example, the diversity in incomes and perceived damages imposes a significant adaptation deficit of 22% lower diffusion of Elevation (dotted curve and pink area in Fig. 2*C*). Elevation is costly, confirming that for more expensive measures financial adaptation constraints matter for households with low incomes or/and low perceived damages.

Furthermore, our unique approach allows to quantitatively compare the inclusion of heterogeneity in financial adaptation constraints (RA_{Het}), with the integration of diverse adaptation constraints that bound rationality by explicitly accounting for socio-behavioral biases ($BA_{Hom/Het}$). Importantly, our results reveal that the diffusion of all three adaptation types is highly sensitive to the switch from *RA* to *BA* behavioral heuristics, which appears more influential for adaptation diffusion than income heterogeneity. Specifically, when comparing RA_{Hom} with BA_{Hom} (solid curves vs. dashed curves, Fig. 2 *A*–*C*), the diffusion of adaptations drops by 14%, 16%, and 40% for Wet-, Dry-proofing, and Elevation, respectively (the pink and green areas combined, Fig. 2). The inclusion of variability in socio-behavioral factors further widens the adaptation deficit by another 11% and 12% in Wet- and Dry-proofing compared to BA_{Hom} (dash-dotted curves for BA_{Het} and the blue areas, Fig. 2 *A*–*C*). The overall adaptation deficit between the optimal level of private adaptation and its uptake by a population of empirically-calibrated boundedly rational households with diverse incomes, perceptions, and social norms from the survey constitutes 25%, 28%, and 40% for Wet-, Dry-proofing, and Elevation correspondingly (solid vs. dash-dotted curves for RA_{Hom} and BA_{Het}, Fig. 2 *A*–*C*). Our results imply that even for individual investment decisions, such

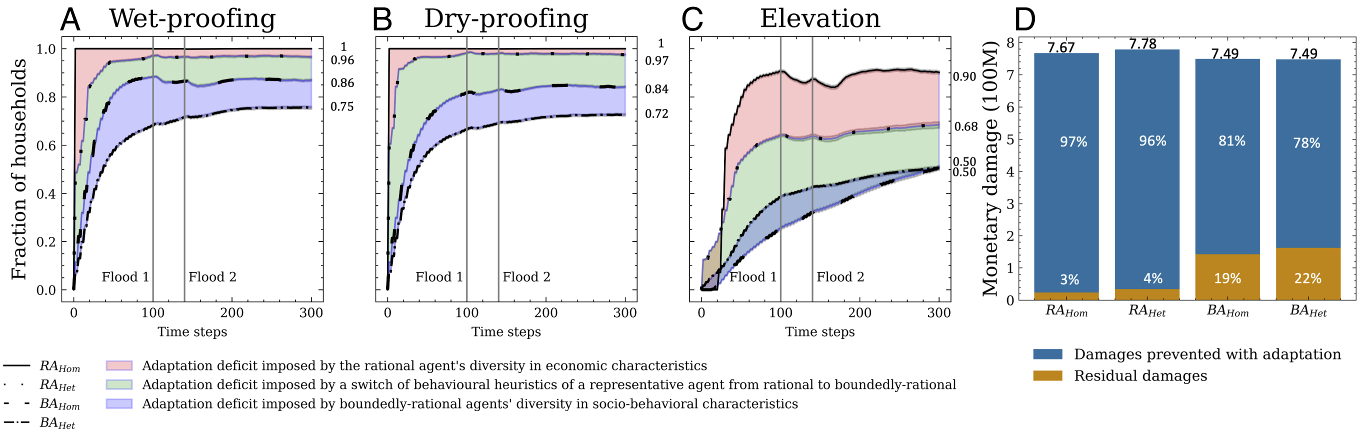

Fig. 2. (*A*–*C*) Adaptation deficit across four behavioral strategies: representative rational agent (RA_{Hom}), rational households heterogeneous in incomes, education and damages (RA_{Het}), representative (BA_{Hom}) and diverse (BA_{Het}) boundedly rational agents. The reported values are averages across the 100 Monte Carlo runs for each of the four behavioral framings, with the shaded areas denoting the SDs. (*D*) Regional damages households experience in case of a hazard, in hundreds of millions \$. The reported values are averages across the 100 Monte Carlo runs for each of the four behavioral framings.

as the three CCA measures, other soft adaptation constrains like affect heuristics, perceived self-efficacy, or social norms are the core source of behavioral uncertainty in the speed and scope of adaptation diffusion, instead of the conventionally scrutinized factors: heterogeneity of incomes and other financial constraints.

A unique feature of CRAB compared to other ABMs (8, 9) is that household adaptive behavior is embedded in the evolutionary macroeconomy. The endogenous technological change in CRAB induces firm productivity and wage growth. Both increase the attractiveness of this coastal region and trigger an inflow of households and firms, leading to growing property values. Consequently, regional damages to households in the event of a flood increase over time, reaching \$749–778 million at the end of the simulation (Fig. 2*D*). Notably, households which behave as rational optimizers prevent nearly all damages via adaptation (RA_{Hom} and RA_{Het}, Fig. 2*D*). Taking a step further by converting emerging adaptation deficits into damages, our analysis illustrates that replacing a representative rational agent by a population with varied incomes and perceived damages makes a difference of 1% in the total prevented damages to households in the region. Conversely, as with adaptation deficits (Fig. 2 *A*–*C*), switching to a different behavioral heuristic and assuming that households follow empirical patterns of decision-making about adaptation, escalates residual damages (BA_{Hom} and BA_{Het}, Fig. 2*D*). Leveraging the survey data, our ABM uniquely estimates the economic costs of soft adaptation constraints as differences in regional residual damages to households emerging from rationally optimal vs. empirically informed adaptation behavior (3–4% vs. 19–22%, Fig. 2*D*). Our new findings quantify that the costs of soft adaptation limits imposed by traditional financial adaptation constraints are 5–6 times smaller than of diverse adaptation constraints (i.e., awareness, social norms, education, financial).

Uneven Distribution of Damages, Adaptation Diffusion and Benefits of Adaptation in a Population. To explore equity implications of hazards and adaptation, we complement the aggregated damage with the analysis of how damages and benefits of adaptation are distributed among different households. The ability of people and societies to adapt is associated with adaptive capacity, which is contingent on economic wealth, education, experience, social institutions, and governance (16). Since the latter three are universal in the CRAB model, we assume that the feasibility of adaptation actions for households depends on their education level and income.[*] Based on this, we distinguish households with Low, Medium, and High adaptive capacities (AC), and analyze whether and how—depending on their initial assets and adaptations taken—their damage and recovery trajectories vary after two severe floods shock the regional economy at steps 100 and 140 (Fig. 3). To compare damages across households, we divide damages (after eventual adaptation) by the households' monthly incomes.

Without private adaptation, damages for an average rational household at the end of the simulation are more than 20 times higher than with adaptation (solid vs. dashed green curves, Fig. 3 *A* vs. *B*). After both floods, there are spikes of damage that fade back to pre-flood levels as households recover (shaded areas under the solid curves, Fig. 3*A*)—the "resilience triangles" (41). Even without adaptation, High AC households recover immediately after both floods (solid red curve, Fig. 3*A*). Low AC households are unable to fully recover following the first flood and maintain higher damages than pre-flood. This is exacerbated after the second flood, making the recovery even longer (blue shaded areas, Fig. 3*A*). Here, CRAB reproduces another stylized fact documented in the empirical literature (12): despite Low AC, households owning the least costly assets and experiencing the lowest direct damages, their recovery is the longest. Thanks to the distinct methodological strength of CRAB that combines both macroeconomy (i.e., endogenous GDP and unemployment dynamics) and individual CCA actions, we identify the mechanisms that lead to the long recovery of Low AC. Our analysis reveals that the resilience triangles for Low AC are the largest not only because these households lack resources to recover quickly (i.e., hardly accumulate savings) but also because they are likely to lose income in the aftermath of a flood due to the bankruptcy of firm agents and increased unemployment. Another original insight with respect to the distributional impacts is the emergent vulnerability of the Medium AC households, which develop the highest relative damages in the population (yellow curve, Fig. 3*A*). While Medium AC agents quickly recuperate the immediate losses after floods, following the second flood, they perpetually shift to a trajectory of higher damages (8% above initial).

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[*] Notably, incomes change endogenously in our agent-based model as households change jobs and as the economy develops through technological innovations, but other things being equal, higher educated agents get jobs with higher wages. Since household education grants priority in the CRAB labor market and is highly correlated with income, we anchor adaptive capacity to the education level.

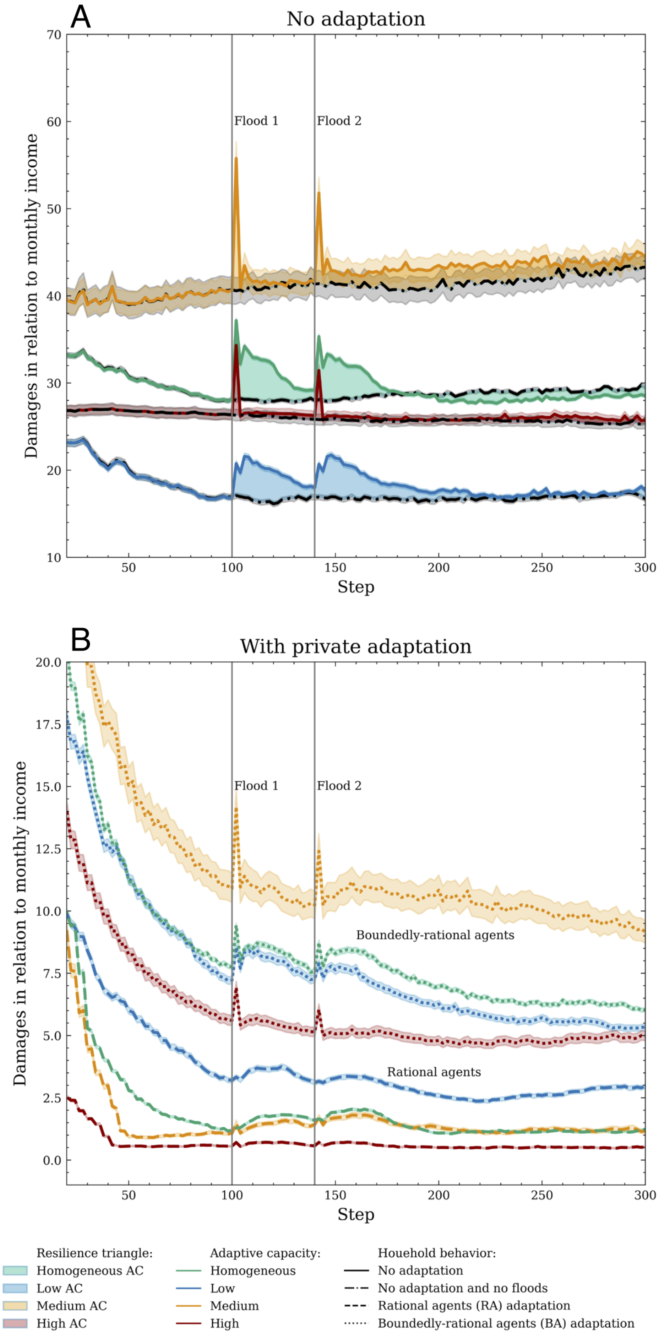

Fig. 3. Residual damages without (*A*) and with households' adaptation (*B*) under rival assumptions about behavior: rational or boundedly rational; assuming all households are the same (homogeneous) or based on empirical distribution of households' characteristics (heterogeneous). The latter is differentiated by adaptive capacity of households. To make residual damages comparable across households with various income, we divide damages by monthly income. All reported values are averages across the 100 Monte Carlo runs.

Assuming that households adapt as rational optimizers, the residual damages for all AC levels decrease over time (bottom dashed *RA* curves, Fig. 3*B*). Previous ABMs (8, 9) also report decreasing aggregated damages due to private action, but our analysis goes beyond to provide insights into the distributional effects of adaptation. Notably, rational High and Medium AC households are more likely to afford the costliest adaptation (Elevation), which drops residual damages nearly to zero (dashed red and yellow curves, Fig. 3*B*). Due to financial constraints, rational Low AC households adapt slow or less effectively. Hence, while adaptation reduces regional damages, its benefits disproportionally benefit High and Medium AC households, with Low AC agents bearing the highest residual damages (dashed blue curves, Fig. 3*B*).

Affected by empirically-revealed behavioral biases and social influences, *BA* households adapt less than rational, and this adaptation deficit raises residual damages 2–10 times depending on AC (dotted vs. dashed curves, Fig. 3*B*). After a flood, *BA* households across all AC levels experience losses but recover almost immediately, confirming the resilience dividend of timely adaptation (12). The ability of the model to test rival behavioral framing provides original insights regarding the uneven distribution of adaptation benefits in the population, revealing that shifting assumptions about human behavior from *RA* to *BA* has implications for inequality. Specifically, residual damages after adaptation of rational optimizers reveal the expected: High AC benefit most from adaptation, followed by Medium and Low AC households (dashed *RA* curves, Fig. 3). This is not the case for boundedly rational households parameterized with the survey data. When soft adaptation constraints, like subjective perceptions and social expectations, curb private adaptation, Medium AC households suffer the highest residual damages (dotted yellow *BA* curve, Fig. 3), as they have already substantial assets to lose but have not yet sufficiently invested in CCA. These findings suggest that even under a nearly complete adaptation uptake in the population, CCA is uneven, and could further exacerbate inequalities since late or less-efficient actions lock-in households to a path of higher damages (Low AC for rational population or Medium AC for the boundedly rational).

Finally, over the past 30 y, scholars have scrutinized the concept of a representative agent (42). Our results show that assuming homogeneity not only fails to identify winners and losers, as commonly discussed in the literature (40), but also misrepresents the behavior of Medium AC households. It is expected to find that the representative agent underestimates the recovery of Low AC households (green vs. blue resilience triangles, Fig. 3*A*). Yet, it is surprising to observe that the representative agent in CRAB undervalues the gravity of losses experienced by Medium AC households by almost 1/3, for both *RA* (yellow vs. green solid curves, Fig. 3*A*) and *BA* (yellow vs. green dotted curves, Fig. 3*B*) populations. It implies that approximating a population of heterogeneous households with a homogenous agent conceals significant losses and misleads policy design.

Behavioral Heuristic Choices Affect the Importance of Uncertain Physical Factors. So far, we have discussed the implications of simulating behavior in the formal model, holding constant the key physical factors that affect damage estimates and adaptation uptake: the fraction of households exposed to flooding and the objective effectiveness of Wet-, Dry-proofing, and Elevation measures. As the baseline values for these factors, we use a conservative fraction of current population in Florida exposed to severe flooding (43), and average values of adaptation effectiveness found in fragmented literature (28). Yet, historic exposure changes with climate change, and the reported data on measure effectiveness (28) vary by 20–80%. Given the uncertainty in these four physical factors, we use SA to quantify their effects on the fraction of households that choose to adopt each adaptation measure (Fig. 4) and on the regional damages to households (Fig. 5). To distinguish their interaction with the households' heterogeneity and behavioral heuristic choices, we perform this analysis thrice, for three rival framings of household CCA behavior: RA_{Hom}, RA_{Het}, and BA_{Het}.

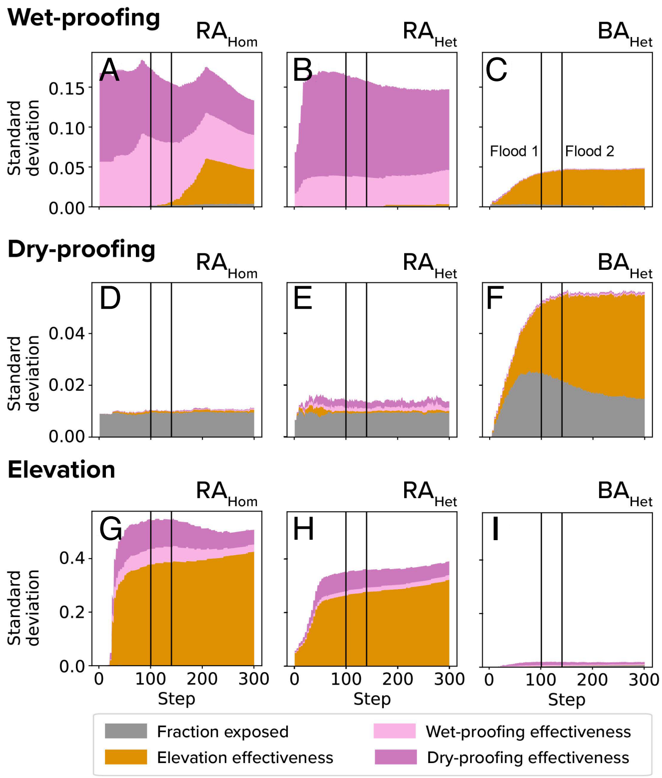

Fig. 4. Time-varying sensitivity indices of the uncertain factors—exposure and objective effectiveness of measures—affecting households' adaptation diffusion. The three rows show the variance in the proportion of households that adopt (*A*–*C*) Wet-, (*D*–*F*) Dry-proofing, and (*G*–*I*) Elevation measures; the three columns show how sensitivity varies per behavioral heuristics: homogeneous and heterogeneous Rational Agents, RA_{Hom} (*A*, *D*, and *G*) and RA_{Het} (*B*, *E*, and *H*); heterogeneous Boundedly rational Agents, BA_{Het} (*C*, *F*, and *I*). The reported values are from the 460,800 Monte Carlo runs.

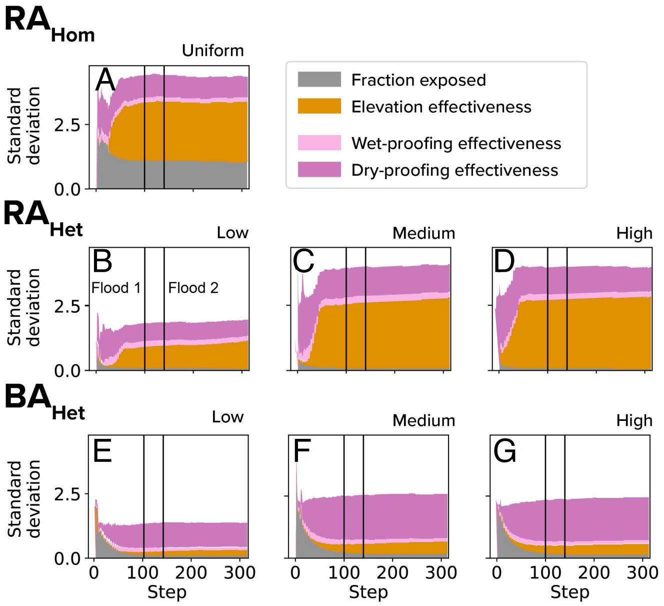

Fig. 5. Time-varying sensitivity indices of the uncertain physical factors—exposure and objective effectiveness—affecting households' residual damages. The three rows plot the proportion of variance in damages of rational (RA_{Hom} and RA_{Het}; panels *A* and *B*–*D*, respectively) vs. boundedly rational (BA_{Het}; panels *E*–*G*) households explained by exposure and measure effectiveness. The three columns for the heterogeneous heuristics show how sensitivity varies across the three adaptation capacity groups (Low, Medium, and High; panels *B* and *E*, *C* and *F*, and *D* and *G*, respectively). The top left figure reveals the effects of physical factors for damages experienced by a representative rational agent. The reported values are from the 460,800 Monte Carlo runs.

Our results show that the variability of adaptation diffusion trends (measured through SDs, Fig. 4), and the factors driving it, differ substantially across adaptation measures (comparing along a column), and across behavioral heuristics (comparing along a row). To measure the effect of each factor, we use sensitivity indices estimating total-order effects on the variance of each output (details in *Materials and Methods* and *SI Appendix*). For instance, in Fig. 4*A*, the sensitivity indices measure how exposure and the objective effectiveness of the three measures contribute to the variability of Wet-proofing adoption as a result of their direct and interactive effects. For rational agents, Elevation effectiveness appears to be the major controlling factor in the fraction of households that choose to elevate (orange, Fig. 4 *G* and *H*), but has less of an effect on the fractions of households that choose to apply Wet- or Dry-proofing (orange, Fig. 4 *A*, *B*, *D*, and *E*). Since Elevation is a costly measure, the importance of its damage reduction effectiveness for its uptake is intuitive. Our distinct approach captures individual trade-offs between different CCA measures in the presence of various adaptation constraints, providing unique estimation of the possible interaction effects. Specifically, if boundedly rational households make adaptation decisions as they report in the survey, we see a reversed effect: Elevation effectiveness hardly matters for the uptake of Elevation but is the predominant factor affecting the households that choose to Wet- or Dry-proof (in orange Fig. 4 *C* and *F*). Similar contrasts are seen when comparing the relative importance of Wet- and Dry-proofing effectiveness (Fig. 4, light and dark pink colors, respectively) across adaptation measures and behavioral heuristics. Hence, a small change in the objective effectiveness of CCA measures is amplified by socio-behavioral factors, like perceived effectiveness or perceived damages, and leads to non-linear effects of physical factors under alternative behavioral framings.

Our results uniquely reveal that socio-behavioral factors mediate the importance of physical factors traditionally thought to be decisive for CCA uptake. Without considering these interactions between physical and behavioral uncertainty, the design of policies could be misguided: resources could be misdirected on factors that are inconsequential, by either investing in collecting data on their effectiveness or in running information policy campaigns. For instance, the uncertainty surrounding the effectiveness of Wet-proofing measures appears to not affect adaptation choices of empirically grounded agents, but matters significantly for rational optimizers (BA_{Het} vs. both *RA* models, Fig. 4 *A*–*C*). We also note that, again, a shift from a representative to a diverse population of rational households, i.e., accounting for heterogeneity of financial adaptation constraints, hardly changes the relative importance of the four physical factors on adaptation diffusion (left vs. middle column, Fig. 4). Yet, a switch to a boundedly rational heuristic transforms the importance of objective factors for CCA uptake (right column). The longitudinal SA also reveals that the relative importance of the four physical factors changes over time. For example, when households mimic empirically reported behavior, the uncertainty in Dry-proofing uptake depends mostly on exposure in the beginning, with the non-linear interaction with effectiveness of an alternative measure (here Elevation) eventually becoming the dominant factor explaining uncertainty of the Dry-proofing diffusion (Fig. 4*F*), highlighting the importance of accounting for trade-offs between different CCA measures households face.

We also quantify the effects of the four uncertain physical factors on potential damages (Fig. 5), across three rival behavioral models (RA_{Hom}, RA_{Hom}, and BA_{Het}) and three levels of individual AC (Low, Medium, and High). Results reveal that the introduction of heterogeneity in the *RA* model changes the relative impact of uncertainty in the fraction of households exposed (comparing panels in Fig. 5 *A*–*D*). This means that in comparison to a representative agent (RA_{Hom}), for rational heterogeneous households (RA_{Het}), the effects of uncertainty in their exposure on the variance of potential damages drops nearly to zero, while the importance of uncertainty in the effectiveness of the three measures becomes more apparent. Accounting for bounded rationality in agent behavior (Fig. 5 *E*–*G*), the relative importance of physical factors shifts again, with damage variance now dominated by uncertainty in the effectiveness of Dry-proofing. Notably for empirically based households (BA_{Het}), if policymakers were concerned only with the diffusion of adaptation measures in the region, our analysis would suggest focusing on communicating and improving Elevation effectiveness (right column, Fig. 4). If they want to minimize regional damages, then policies should focus on Dry-proofing effectiveness (bottom row, Fig. 5). Therefore, complementing longitudinal SA of damage estimates (Fig. 5) with monitoring the diffusion of various adaptations (Fig. 4) is essential to assess what policy instruments improve what type of CCA for what households, and to make informed trade-offs when deciding on CCA policy design.

Discussion

Methodologically, sustainability science has been long concerned with unsatisfactory representations of human behavior in formal models of human-natural systems (25). By combining agent-based simulations, household surveys, and exploratory modeling we demonstrate that the traditional use of a representative rational optimizer overestimates adaptation diffusion and overlooks inequalities in the distributional impacts of hazards and of adaptation. For CCA specifically, an understanding of how macro-outcomes change as the richness of microbehavior in models addresses a number of key research priorities (5).

This article advances methods for sustainability science in several ways. First, responding to the calls for methodological advances in ABM (7, 9), we provide a solid example of using surveys to populate agents in formal models with data on socio-behavioral factors that environmental psychology considers foundational for representing behavioral changes. Complemented with exploratory modeling, this approach offers a solid systematic SA of rival behavior framing with nearly 500 thousand simulations exploring interactions between behavioral and physical uncertainties. Second, unprecedentedly this ABM embeds fine-scale modeling of households adaptation behavior in a complex evolving macroeconomy prone to hazards, introducing firms as key agents defining regional economic development, endogenous changes in households incomes and in unemployment. This permits combining standard to agent-based modeling of informal social influences with the evolution of formal market institutions, which jointly either boost or hinder the speed of adaptation diffusion and the uneven distribution of its benefits. Third, departing from the common practice of reporting aggregated population-level results of household adaptation (7, 9, 44), we explicitly trace trade-offs among various adaptation measures and visualising results per individual adaptive capacity to enable substantiated discussions about equity and tailored policy designs. These methodological advances offer insights for the science and practice of CCA, and for sustainability modeling efforts that aim to capture human behavior in nature–society systems.

Quantifying Soft Limits and Speed of Individual Climate Adaptation. Assessing the speed of adaptation uptake and its soft limits is among the key challenges for CCA science and policy (5). Our unique approach goes beyond heterogeneity in financial adaptation constraints, which has been the main step in advancing over the representative rational agent model of human decisions in contemporary CCA literature. The switch from the *RA* to *BA* framing of human decisions fundamentally impacts all model outcomes—adaptation deficits, regional damages and even the effects of uncertain physical factors like hazard exposure and objective adaptation effectiveness. Leveraging theory and survey data, our results reveal that even for investment decisions, soft adaptation constraints like affect heuristics, self-efficacy, and social norms (i.e., bounded rationality) are the core source of behavioral uncertainty in the speed and scope of individual adaptation diffusion. Conversely, the effects of heterogeneity in incomes and other financial constraints are not as essential (at least for households in advanced economies) as commonly assumed in the literature. Following the patterns in the survey data, the behavioral (e.g., risk perception, perceived response-efficacy) and social (e.g., descriptive norms) factors either facilitate or curb individual intentions of *BA* agents to adapt. Moreover, in our model, some of these adaptation constraints change over time for *BA* agents who learn, for instance from their experience with CCA measures or floods (in contrast, *RA* agents do not learn). Accounting for both diverse adaptation constraints and learning explains the difference in macro-outcomes of *BA* vs. *RA* simulations.

Role of Institutions in Shaping Equity and Socio-economic Resilience. The individual behavioral changes described above are also affected by institutions on meso (social norms) and macro (economy) levels. Tracing the evolution of these institutions in our framework enables going beyond conventional findings that High AC households adapt quicker and suffer less damage than their Medium and Low AC peers. Instead, we explicitly model the mechanisms that amplify or reduce existing inequalities.

Besides individual learning, *BA* households in CRAB also observe the evolution of descriptive norms. As the number of peers pursuing a specific CCA grows in an agent's social network, the prevailing local social norm shifts from "non-adaptive" to promoting CCA behavior. Hence, *BA* households with larger social networks full of early CCA adopters adapt quicker and better than those with smaller networks dominated by laggers, causing agents to benefit differentially from adaptation. Besides speed, which CCA measure households adopt also matters. While ABM literature typically models one type of household CCA, our results reveal non-linear trade-offs between the three CCA measures. The social amplification[†] influences the speed and type of CCA adopted, both of which matter for damage reduction in our results, and hence for the (un)even distribution of CCA benefits.

The macroeconomic mechanisms also have differential impact on disparities. In CRAB, households interact with firms that provide jobs. Household incomes change endogenously depending on the firms' economic performance, implying that labor market institutions expedite the recovery of some households, but lock others into a path of increasing inequality. Specifically, firms hit by floods decrease their production due to destroyed assets and face higher costs due to productivity losses. Those who go bankrupt, leave their workers unemployed. These indirect damages are milder for individuals with High AC who find another job easier due to their higher education; low-educated Low AC stay unemployed longer, which slows their recovery and hampers opportunities to adapt on time due to lacking savings. This unique feature of CRAB—integration of households in the

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[†] Only for *BA* households; *RA* do not learn and are not prone to social influences.

macroeconomy—permits tracing another macroeconomic mechanism: indirect benefits of CCA. Besides protecting households from direct damages, private CCA diminishes their post-flood repairs, reducing shocks to goods' markets. It helps firms avoid bankruptcies, reducing labor market shocks and unemployment in the aftermath of a flood. This result reinforces previous statements on the importance of bottom-up CCA actions to build climate-resilient societies (6), including the prevention of business interruptions essential for socio-economic resilience (45). The indirect macroeconomic effects of CCA—faster post-flood recovery, fewer damages after repetitive hazards, and reduced unemployment—also known as resilience dividends, could lift people and regional economies instead of locking population into long-term structural vulnerabilities. As such, our results demonstrate macroeconomic co-benefits of private CCA, with implications for policy design that should embrace a systems' perspective, going beyond direct damages to account for cascading indirect effects for various stakeholders.

Tailored Policies for Closing the Adaptation Deficit. While many ABMs model heterogeneous agents, most report only population-level outcomes (44). Leveraging on this natural strength of ABMs, we present results differentiating per household AC. Our analysis supports previous findings that shocks disproportionally impact Low AC who have the longest recovery despite suffering the lowest damages. Surprising was to find that Medium AC, who have assets to lose and sometimes enough finances, postpone adaptation due to the awareness or self-efficacy constraints. These soft constraints are the main reasons the damages pathways for Medium AC (and the overall adaptation deficit) vary so much for *BA* vs. *RA* agents.

Compared to the optimal, the insufficient level of adaptation pursued by *BA* households with empirically grounded behavior is so significant that it calls for tailored CCA policies that explicitly motivate private adaptation. Our analysis reveals different channels via which CCA policies could reach various vulnerable households by removing their adaptation constraints. For example, Low AC households will benefit from tailor-made subsidies (e.g., anchored to property values/incomes) for most effective (instead of just any) CCA measures and from uplifted education. Conversely, Medium AC households will benefit from information policies with personalized narratives appealing to perceptions and social identity. Such strategies can complement the communication of climate-driven risks to avert households from locating in climate-sensitive regions or investing too late in private CCA. Designing tailored policies to overcome such soft adaptation constraints could result in nearly a fivefold drop of residual damages per household according to our analysis.

Importance of Behavioral Uncertainty for Policy Design . Uncertainty is an inherent component of decision-support for CCA policy, which has so far heavily focused on exploring implications of various government-led adaptation choices (3) or physical factors (2), omitting behavioral uncertainty of private adaptation. The analysis here considers both uncertainties in physical factors and epistemic behavioral uncertainty—the rival framing from rational to empirically grounded and from homogeneous to heterogeneous populations.

Our analysis demonstrates that fundamental differences between *RA* vs. *BA* behavior framings are critical for CCA, and for nature–society systems in general, given similar observations for other sustainability applications (10, 11). Additionally, our longitudinal SA shows that behavior framing alters the more predictable variance imposed by physical factors that are conventionally considered crucial in CCA policy (exposure and objective adaptation effectiveness). While introducing heterogeneity in financial constraints (RA_{Het} vs. RA_{Hom}) matters, it is the switch to a realistic representation of behavior shaped by diverse adaptation constraints (RA_{Hom} vs. BA_{Het}) that fundamentally changes how consequential the uncertainties in physical factors become. Notably, the physical uncertainties interacting with behavioral uncertainty manifest differently for households of different adaptive capacities (more damage variability for Medium and High AC) and different CCA measures. For example, for BA_{Het} households, elevation efficacy (and lack thereof) is the most critical factor in how many households choose to apply Wet- and Dry-proofing. This is not the case under the assumption of agent rationality.

When it comes to model-based policy design to address CCA, this implies that assumptions about how we represent human decision-making processes influence our expected adaptation outcomes. This is a finding already highlighted in literature widely, but we stress two additional nuances illuminated by this unique combination of methods in this study. Behavioral assumptions also shift what we consider to be our "X factors"—the key variables that might undermine adaptation progress and that we need to monitor and prepare for. An unrealistic representation of human behavior might mislead modelers and policy makers to direct efforts on factors that are in fact inconsequential. For example, if we design CCA policy under a simplified premise of human homogeneity and rationality (in our case, the RA_{Hom} model), we might be misled in either investing in the wrong data collection campaigns or in running information policy campaigns focused on the effectiveness of measures that make no difference. A particular finding we highlight here is that the degree of household exposure might not be as critical in reducing residual damages as other soft socio-economic limitations. Instead, non-linear interactions between alternative CCA measures become apparent, for instance, when households start to substitute CCA measures as uncertainty about their effectiveness changes.

Generalizability of Findings. Being applied to CCA, our modeling framework advances the literature in addressing one of the most sought for challenges in sustainability sciences: representation of human behavior in formal models. Grounded in social science theories, our ABM encompasses generic mechanisms shaping both macro- and micro-dynamics (27). We validated macro-dynamics against stylized facts (*SI Appendix, Model Validation*), which are generalizable for market-based economies characterized by economic growth and increasing population. For micro behavior, we employ the prominent psychological theory (PMT), which assumes human behavior in the risk context is shaped by perceived awareness (of threat), self-efficacy, and social norms among other socio-behavioral factors. PMT has been shown to explain generic mechanisms behind CCA behavior better than alternative theories[‡] and has been validated against empirical data worldwide (13–15). While we used surveys to partially parameterize factors of household CCA behavior for a specific population, the underlying mechanisms of behavioral change under risk are generic. Hence, the derived insights—that socio-behavioral factors rather than income heterogeneity alone matter for macro-outcomes, that these factors contribute to shaping inequality, and that they interact with uncertainty of

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[‡] Alternative theories of behavioral change could be better suited in other contexts where risky outcomes are absent and different cultural norms or habitual behavior is prevalent. In those cases, behavioral change mechanisms and the corresponding simulation outcomes could vary.

physical factors—are likely relevant beyond this case-study and this particular hazard. Consequently, the presented framework could be applied to similar situations, where the behavioral change of interest has not yet happened, since the mechanisms behind the factors driving potential behavioral changes (at least in the risk context) are encoded and could be activated as the simulation unfolds. Naturally, the specificity of those interactions in other contexts should be ascertained with behavioral microdata.

The detailed behavioral data also enables us to identify which of the socio-behavioral factors and constraints matter the most for shaping soft limits to adaptation. While it is crucial for achieving context-specific results, we believe that empirical survey limitations are not always a hindrance to the application of such methods for other cases or sustainability challenges. Currently, behavioral data is becoming increasingly available via literature publishing case-based surveys on pro-environmental behavior, meta-analyses or cross-cultural surveys (15, 31, 46), and open-access databases (e.g., World Risk Poll[§]) making such advanced, behaviorally-rich models more feasible. This said, as with ecological, hydrological or climate models, theory-driven mechanisms and secondary data only help elicit rough system dynamics and draw conclusions in broad lines. Nonetheless, high-quality analyses of human behavior in sustainability science models necessitate high-quality data on the behavior in question.

Limitations and Future Work. Our modeling work can be expanded in several ways. First, the analysis would benefit from a more comprehensive spatial representation of climate shocks aligned with hazard maps corresponding to downscaled Representative Concentration Pathways scenarios (1). Future work could also explore hydrological modeling of floods under various climate scenarios (47) and perform a comparative analysis for other coastal regions, which may require extending to other economic sectors and empirical calibration of sector-specific impacts of hazards. Additionally, the model would benefit from including firms' CCA decisions.

Second, while our exploratory modeling accounts for the effects of epistemic uncertainty and stochasticity, it does not consider parametric uncertainties in the socio-economic system. Performing global SA on empirically defined weights for different behavioral factors might interfere with the theoretical grounds of the behavioral model. Additionally, methodological innovations in sampling and processing large uncertainty ensemble runs would enable better comprehension of the effects of such uncertainties. Furthermore, although we capture changes in agent behavior based on their updated flood experiences, taken CCA actions and evolving social norms, future work could also account for fundamental changes in preferences (i.e., here, weights are estimated using only a snapshot of past data). Future research could delve into how individual perceptions and preferences evolve over time, perhaps employing panel survey datasets from different contexts (14, 48). Given the complexities of real-world behavior, other "dynamic" methods of data collection, such as laboratory experiments, randomized control trials, and serious gaming—all of which have seen integration with ABMs (49)—might offer deeper insights when applied to CCA contexts.

Last, such combinations of methods could be used to quantify soft adaptation limits or tipping points at which individual objectives or societal needs cannot be secured from intolerable risks through adaptation (5, 17). Identifying such social tipping points in CCA could also help design policies for transformational adaptations, such as planned and equitable relocation when certain locations reach their adaptation limits (50). ABMs are already accustomed to combining public government-led adaptation with private actions (8, 9) to explore both synergies and unintended effects between public and private adaptations.

Materials and Methods

To analyze the role of behavioral assumptions on household CCA and regional damages, we combine an evolutionary economic agent-based CRAB model with household survey data and with exploratory modeling. CRAB simulates socio-economic dynamics of regional agglomeration economies exposed to climate-induced risks (for more information about the theoretical foundations of the model see ref. 23). It features a regional economy exposed to floods and populated by heterogeneous households and firms that interact, learn, and endogenously decide what to do (e.g., how much goods to produce, whether to adapt or relocate). We employ survey data from Florida, US ($n = 965$) to parameterize household behavior (14). Considering the high uncertainty surrounding hazard, exposure, and vulnerability of the regional economy, we also perform an extensive SA on the fraction of population exposed, and on the effectiveness of private flood-proofing measures.

Socio-economic Structure. The CRAB model builds upon the evolutionary economic tradition (26, 51). Here, the model features a three-sector regional economy with four classes of heterogeneous agents: households, and capital-good, consumption-good, and consumption-service firms. Firms and households dynamically interact in decentralized labor and good/service markets. The number of agents changes in the course of the simulation depending on the migration of households and entry/exit of firms. The region is divided between hazard-prone and safe areas to mimic the greater Miami case, with 40% of agents exposed to floods. Floods hit agents in the hazard-prone area, destroying households' properties, firm inventories, and machines. Households living in the hazard prone-area can take multiple CCA actions to protect themselves.

Firms. The capital-good sector invests in R&D to discover more productive technologies. The latter generates a "Schumpeterian" creative (innovative) destruction process, which is the engine of economic growth. Capital-good firms then advertise their machines via "brochures" to possible customers: consumption-good/service sectors. Once orders are computed, capital-good firms produce machinery using labor. The consumption-good/service sector combines labor and capital to produce a homogeneous good/service. These two sectors follow the same decision-making process using adaptive heuristic demand expectations and fixed capital-output ratios to achieve desired production and capital stock level. Importantly, if capital stock is insufficient to satisfy the desired production, new machines are ordered comparing the "brochures" firms are aware of. In addition, following a pay-back rule, current machinery can also be replaced by more productive ones. The consumption-good sector differs from the service sector in their capital-output ratios. We loosely parameterize this regional economy based on the data for Florida, implying that the consumption-service sector is more capital-intensive than the consumption-good sector (52).

Households. Households have multiple socio-economic and behavioral characteristics derived from survey data: property values, education, and initial savings, as well as the influence of social norms. Households spend a fraction of their income if employed, while unemployed households spend their entire unemployment benefits. Savings accumulated over time are spent on protective CCA actions and to repair flood damages. The latter depends on the household property value and the damage coefficient. The value of the household property is indexed to the region's average wage, thus increasing over time. The damage coefficient is calculated overlying flood depth and depth-damage curves for residential buildings, using US data (53).

Rival Framing of Human Behavior. The model allows for comparing CCA protective actions of rational, fully informed (*RA*) and of boundedly rational (*BA*) households. In the *RA* framing, households compute Expected Utility by weighting the costs and benefits of undertaking a CCA action against no-action and choosing the highest-utility option. In the *BA* framing, we assume that

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[§] https://wrp.lrfoundation.org.uk/.

households behave as suggested by PMT. Using Florida survey data, we run a Logit regression to estimate effects of relevant socio-behavioral attributes (*SI Appendix, Model Calibration*). We also differentiate between homogeneous and heterogeneous populations of both *RA* and *BA* households, using either the survey averages or drawing values from empirical distributions of corresponding survey attributes. For example, for BA_{Het} households, we use effects from the Logit model to specify the relative weights for each socio-behavioral attribute. Each BA_{Het} household multiplies these weights by their own heterogeneous attributes to estimate a probability to adopt each of the three CCA measures. Since not all households who intend to adapt actually take action, we assume that households in CRAB adapt only if this probability is higher than a threshold randomly drawn between 0 and 1 (*SI Appendix, Households*). Households living in flood-prone areas perform this calculation each time step for all the affordable CCA measures that they have not yet implemented. It is important to note that household's probability of adaptation can change over the course of the simulation due to evolving values of the socio-behavioral factors. One factor affecting such probability is the implementation of a measure. Specifically, past undergone measures decrease the probability of future adoption of other measures directly and also indirectly by decreasing expected damages. The diffusion of a particular measure can also affect other households' decision-making by updating the descriptive social norm in own network as new peers undertake the measure. Additionally, the experience of flooding also affects households' probability of CCA. While these changes in attributes are limited in scope, they aim to capture the possible behavioral trajectories arising from our models.

Model Calibration. We calibrate our regional economy to resemble a coastal agglomerated area in the southeast US, such as Miami-Dade county. In addition to the survey data, we employ publicly available statistics. We include 3,000 households created from the survey data, i.e., about 0.5% of the total owner-occupied properties in the county. We calibrate firms according to the current business-to-population ratio. To calibrate the capital intensity of firms from the three sectors in CRAB, we apply constant US capital-output ratios from a macroeconomic model (52). To parameterize heterogeneous household behavior, we generate a synthetic population by conditionally sampling household attributes from the survey data using first moment and cross-correlation among variables as the fitness criteria (*SI Appendix, Model Calibration*). When the population is assumed to be homogeneous, the attributes' mean value is used for all households, which will then have the same socio-economic and behavioral initial characteristics. We also employ national statistics to divide household expenditure between goods and services. Last, we model the number of agents living in flood-prone areas according to the percentage of properties likely to be affected by a major flood in the next 30 y in Miami-Dade county. We consider two extreme floods of 3-m high hitting this regional economy at fixed time steps (100 and 140), equivalent to a storm surge generated by a category five hurricane hitting the low-lying flood-prone areas.

Institutions. Households and firms interact via formal economic institutions (capital, labor, and goods/services markets) and informal (social networks) institutions. In the capital market, capital-good firms send brochures containing the price and productivity of their machines to existing customers and new, randomly selected, potential customers. Consumption-good and -service firms seeking to buy new machines compare the brochure they received and select the supplier with the best price-quality ratio. In the labor market, firms assess their labor demand and post available vacancies or fire the surplus of workers. Unemployed households, sorted by education level, select a subsample of available vacancies and choose the one with the highest wage. Hence, households with higher education will get better-paid job opportunities. Wages are then partially spent on goods and services. The aggregate household expenditure in good and service markets defines the local demand in the coastal region. Local demand is summed to export demand and assigned to firms according to their market share. The latter depends on their competitiveness, which, in turn, is calculated according to their prices and unfilled demand. Firms' market share evolves via quasi-replicator dynamics (*SI Appendix, Firms*). Furthermore, *BA* households are influenced by social norms, i.e., unwritten rules characterizing how appropriate a certain behavior is within a social group. Our survey elicits the influence of both descriptive and injunctive social norms, which we parameterize in the CRAB model using the estimated logit effects (*SI Appendix, Model Calibration*). These effects serve as weights impacting individual intention for CCA. For each household in CRAB, these weights are multiplied by the number of contacts in the individual's social network that have undertaken the specific CCA actions (*SI Appendix, Household*). To instantiate a social network, each household in CRAB links to a number of other agents, and this number we draw from the empirical distribution reported by our survey respondents in Florida. This social network serves as a medium for households to learn about protective actions undertaken by their peers the uptake of which evolves as the simulation unfolds.

Entry and Exit of Economic Agents. The agglomeration process in the regional economy in CRAB is endogenous, with households' and firms' entry (in-migration for households and establishment of firms) and exit (out-migration for households and bankruptcy for firms) processes dependent on how the regional economy performs. Specifically, a migration process linked to regional economic indicators regulates the number of incoming/outgoing households. Aligned with empirical evidence, we use the difference in income per capita, and the unemployment rate (54) as indicators of the regional attractiveness for household agents. In a nutshell, an economy with a growing income per capita and a low unemployment rate attracts new households sampled from the synthetic population pool and added to the incumbents. Conversely, a stagnant economy will push households to migrate elsewhere. Households also affect the creation of new firms from the bottom-up. In particular, an employed household decides to create its own firm if the profits of its current employer exceed a certain threshold for a number of consecutive periods. Firms with quasi-zero market share and lack of resources are assumed to go bankrupt and are removed.

Exploratory Modeling and Sensitivity Analysis. We create a large set of alternative model assumptions, representing plausible uncertainty in the estimates of the model's physical factors: flood exposure and the effectiveness of the three adaptation measures (Wet-proofing, Dry-proofing, and Elevation). We use this set perform global SA to identify factors explaining the variability of critical model outputs. To causally apportion output uncertainty to uncertain physical (input) factors we use Sobol' variance decomposition (55). Assuming parametric independence and uniform distributions, we generate a set of 1,536 parameter combinations across the parameter ranges as detailed in the *SI Appendix*. These ranges are informed by literature estimates (see ref. 28 and references therein for effectiveness). We note that even though the term "sensitivity analysis" might be common in the literature, it is often a misnomer or it refers to so-called "one-at-a-time" analyses that miss the interactions uncertain factors might have, or they are "local" in that they only test deviations from nominal values. Even though these applications are common due to their computational ease, the analysis performed here examines the full parametric space as well as parameter interactions. The analysis is also exploratory in nature (referring to exploratory modeling as articulated above), as it moves well beyond literature estimates to assess the effects of uncertainty. To do so, we intentionally expand the parametric range we explore to capture consequential interactions that might exist in more extreme regions of the parametric space, such as the entire population being exposed. Each exploratory ensemble is applied to three alternative behavioral heuristics (RA_{Hom}, RA_{Het}, and BA_{Het}) to assess how the importance of each factor changes under rival behavioral framings. For each parameter combination we also perform 100 Monte Carlo runs to preserve the effects of stochasticity, creating a total of 460,800 model simulations for the exploratory analysis alone. We calculate total-order Sobol' indices measuring the total contribution of each factor both individually and through its interactions with other factors. To do so, we average the 100 Monte Carlo runs across every time step for every parameter sample and for every uncertain outcome (i.e., the fraction of households that choose each adaptation measure and the potential damages of households with different levels of adaptive capacity). We then calculate the indices using the Sobol' method implementation in the SALib Python package (56). Each (total-order) index is estimated for every time-step in the simulation, resulting in an estimate of "time-varying" longitudinal significance. This allows us to detect changes in relative importance across all the years, indicative of changes in regimes or other fundamental system shifts. Time-varying sensitivity analyses have been more commonly applied in other modeling domains (38), but are not prevalent in the ABM literature, especially in experiments at the computational expense of the one presented here.

Data, Materials, and Software Availability. The agent-based model code and the global sensitivity analysis scripts have been deposited at GitHub: https://github.com/SC3-TUD/PNAS-Uncertainty-in-Boundedly-Rational-Climate-Adaptation/tree/main (57). The questionnaire and the minibatch of the household survey data have been deposited at the DANS (Data Archiving and Networked Services) Archive: https://doi.org/10.17026/dans-x9h-nj3w (58). The statistics related to the survey data required to reproduce the results are provided in the Supplementary Information to this article.

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Author contributions: T.F. designed the research project; A.T., T.F., and A.H. developed the study; A.T. and T.F. developed the agent-based model; T.F. and B.N. designed the survey; A.T. performed agent-based simulations and the basic sensitivity analysis; A.H. performed the global sensitivity analysis; and A.T., T.F., A.H., and B.N. wrote and edited the paper.

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