ANTHROPOLOGY

Bad year econometrics: Agent-based modeling of risk management strategies under varying regimes of environmental change

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Resilience—the ability of socio-ecological systems to withstand and recover from shocks—is a key research and policy focus. Definitions of resilience differ between disciplines, however, and the term remains inadequately operationalized. Resilience is the outcome of variable behavioral decisions, yet the process itself and the strategies behind it have rarely been addressed quantitatively. We present an agent-based model integrating four common risk management strategies, observed in past and present societies. Model outcomes under different environmental regimes, and in relation to key case studies, provide a mapping between the efficacy (success in harm prevention) and efficiency (cost of harm prevention) of different behavioral strategies. This formalization unravels the historical contingency of dynamic socio-natural processes in the context of crises. In discriminating between successful and failed risk management strategies deployed in the past—the emergent outcome of which is resilience—we are better placed to understand and to some degree predict their utility in the contemporary world.

INTRODUCTION

Resilience—widely applied across the biological and human sciences—is an emergent property capturing a given system's ability to withstand and recover from external and internal shocks and downturns (*1–5*). Environmental stressors may come in different forms from regular environmental fluctuations, such as climatic cycles of cooling or warming, to sudden, high-intensity shocks such as tsunamis, earthquakes, droughts, or volcanic eruptions and their associated aftermath. Furthermore, these shocks inevitably occur against a backdrop of varying environmental regimes, including the high-amplitude and high-frequency climate fluctuations of the Pleistocene or the Anthropocene to periods of more moderate cooling and warming during most parts of the Holocene. Correspondingly, the types of behavioral responses or strategies that could be deployed in the face of each stressor differ considerably (*6*, *7*). *Homo sapiens* have an evolved ability to invent, maintain, and accumulate knowledge and skills, and we often nest these individual adaptive responses within the wider context of a social group. Thus, human societies manage these risks primarily through the application of various culturally and technologically mediated resilience strategies (*8*, *9*) and institutions (*10*). The social interactions involved in developing and maintaining these strategies, such as a group's collective memory maintained through oral traditions or specialized skills and knowledge required for ensuring effective adaptation in times of crisis, are critical for their success and have received increased attention in recent literature (*11*, *12*).

In representing so many completed natural experiments, the archeological record is uniquely suited to the study of socio-ecological resilience as it covers not only the widest range of environmental regimes of any dataset but also a highly diverse suite of societal responses that represent a substantially broader array of behavioral strategies compared to those of the present or recent past (*13*). While studies of past resilience are plentiful, the concept has, until recently, been predominantly used as a framing device (*14–17*) rather than a formal investigative framework [but see notable exceptions (*7*, *18*)]. In part, this rests in the conceptual and methodological diversity associated with the notion of resilience [c.f. (*19–21*)] and the active resistance of some against formalization (*22*). At the same time, fields such as ecology or urban studies have developed these formal measures, methods, and models to study resilience with substantial knowledge gains over the last few decades [e.g., (*2*, *23–25*)]. It is only recently that disciplines studying the human past adopted some of these formal methods. Moving forward from case study compilations and programmatic statements (*26*, *27*) requires an abstract formalized framework that enables researchers to explore long-term resilience of various groups through a common dynamic model.

We have long recognized that resilience is part of complex dynamics involving nonlinear interactions between multiple actors as well as socio-natural mechanisms that result in non-trivial, emergent system properties at different analytical scales [for a historical overview see (*2*)]. These properties make resilience a prime example of a research topic that requires formal modeling methods to understand the underlying mechanisms and their interactions, to test the predictions of the model against available datasets, and thus to explain patterns and processes of past histories. Equally, the nonlinear relationship among local individual adaptive responses, the emergent dynamics of these in wider contexts of social interactions, and the resulting effects on the system as a whole call for bottom up modeling techniques such as agent-based modeling that enables bridging individual and global scales. Conceptual models, such as that of Blaikie *et al.* (*28*), recognize access to resources and social as well as physical network capital as the main axes of resilience. This perspective aligns directly with the risk-management strategies to climatic change—and their archeological proxies—first identified by Halstead and O'Shea (*27*): (i) mobility, (ii) infrastructural investment (such as storage or irrigation facilities), (iii) economic adjustment (e.g., intensification or diversification of a group's subsistence base), and (iv) exchange (of goods and services in social and market networks). These four resilience strategies are repeatedly discussed

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in the archeological literature to explain how different behaviors could be favored over others given specific spatial and temporal patterns of environmental stress [see also (*14*, *29*, *30*)].

Here, we systematically evaluate the interaction between these behavioral strategies and diverse spatial and temporal environmental conditions that challenge groups' resilience capacity. Our GoodBYE agent-based model incorporates three key dimensions: the spatio-temporal variability of the stressors, the different strategies human societies engage in to offset them, and the cost-benefit balance that needs to be maintained for survival. We demonstrate the model's heuristic utility in relation to archeological case studies that comparatively consider human responses to past volcanic eruptions (i.e., sudden shocks) and the contrasting fates of Inuit foragers and Norse colonial settlers in Little Ice Age Greenland (i.e., slow-onset stress) and evaluate the overall patterns suggested by the model against a cross-cultural sample of ethnographically documented societies.

Theoretical framework

Following early and influential definitions of ecological resilience (*1*), the broader concept of resilience spread to neighboring disciplines. In anthropology, an application of resilience theory was initiated as early as the late 1970s, when Yellen (*31*) argued that Ju/'hoansi (referred to as !Kung by Yellen) peoples' flexible social dynamics and associated rapid mobility reflected resilience in the face of their challenging desert adaptation. This was further broadened to a general framework using the language of risk management with the foundational bad year economics (BYE) conceptual model (*27*), where the four key cultural responses of human groups were described as "buffering mechanisms" that allowed societies to cope with ecological risk and uncertainty. This framework was later translated into the language of resilience by Redman (*26*), thus linking it—terminologically at least—to resilience research in other disciplines. This enabled its application to a wide range of contexts, from hunter-gatherer societies to urban communities [for an overview, see (*14*, *16*)].

The basic premise of resilience theory is that since the spatio-temporal structure of a given stressor can be often reliably understood, the response mechanisms could also be mapped with considerable accuracy and temporal depth (*26*, *27*, *32*). Thus, resilience strategies were described not only as variable strategies that different societies had developed but also as adaptive solutions to specific patterns of spatial and temporal variability in resource needs. Four BYE strategies, which each allowed human groups to better cope with scarcity and shocks and effectively manage risk, are commonly evoked: (i) mobility, (ii) economic adjustment of the subsistence strategy (e.g., diversification or intensification), (iii) infrastructural investment, and (iv) exchange (i.e., dependence on support via social networks) (Fig. 1). Each of these risk management strategies comes with a unique set of costs and benefits against different types of risks. In addition, conflict can, in principle, be seen as a last-resort strategy to meet escalating risks, albeit one where lives are at stake; it will not be considered further here, although an increase in violence may be seen as one outcome of risk mitigation failure [(*33*, *34*), but also see (*35*)].

Conflict aside, here, we describe the four broad behavioral strategies that can be applied largely independently from each other may leave clear material signatures in the archeological record and whose application will determine a given society's resilience.

Mobility has long been seen as a key trait of many societies, as the ability to move on from an area experiencing resource failure is perhaps the most straightforward strategy for responding to environmental fluctuations both spatial and temporal. Halstead and O'Shea note that the cost of this strategy is a high premium put on information gathering so that appropriate places to move to are already known when the time comes (*27*). There is also an additional resource cost to moving extra distances beyond a group's typical foraging range. The latter cost, in particular, likely constrains the overall population density as well (*36*, *37*).

Economic adjustment can be achieved through multiple means depending on the nature of the resource on which it depends, including diversifying the economic activities, or intensifying resource extraction methods. Diversification could manifest itself, for example, in broadening the diet breadth to include other resources that may not be as susceptible to environmental shortfall or engaging in economic activity beyond one's core offerings to weather market downturns. In effect, this is a strategy that could cope with temporal variability more so than spatial variability, although exploring differences in the spatial distribution of the alternative resources is also possible. The optimal foraging theory literature has already defined how the economics of this strategy function, with many well-described examples of, for example, foraging societies (*38*, *39*). A related strategy of intensification involves investing extra effort to increase the return rates of a given key resource. This could be in the form of additional time, energy, risk, or investment. In whichever form, extra investment could serve to bring in a greater return rate, although diminishing returns on investment is an obvious downside. There is also the risk of overexploiting the environment leading to further deepening of the crisis, e.g., through depleting soils, triggering erosion, causing localized extinctions, or destabilizing ecosystems (*40*).

Infrastructural investment is more common in contexts with predictable but seasonal periods of resource availability, and, in most cases, it is also mutually exclusive with mobility. Investment in infrastructure allows societies to capitalize on resources when they are available for example by storing the surpluses for later periods when resources are less plentiful (*41*, *42*) or investing in flood defense structures ahead of storm surges (*43*, *44*). Infrastructure is less useful for spatially variable contexts as it is usually not easily portable. The important difference to other resilience strategies is that the costs, which may include the extra effort and time required to acquire the surplus and to build the infrastructure (e.g., caches, silos, irrigation infrastructure, and flood defenses), has to be paid in advance and may prove unnecessary if the crisis does not materialize. In addition, any infrastructure also has an inherent risk of loss through spoilage, gradual decline, or theft.

Exchange, and the related activity of maintenance of social networks, during times of resource stress is considered a hallmark human adaptability (*45*, *46*). This resilience strategy is highly flexible and thus may be beneficial during any spatio-temporal environmental variation but is particularly useful for unpredictable temporal shifts in resource availability as long as the social network has been maintained. It relies on an established societal system of reciprocity between exchange partners, which, depending on the system, could add greater complexity to the costs and benefits. The costs involve not only the effort of maintaining the social network but also the movement needed to engage in exchange when needed and the cost of eventual reciprocation.

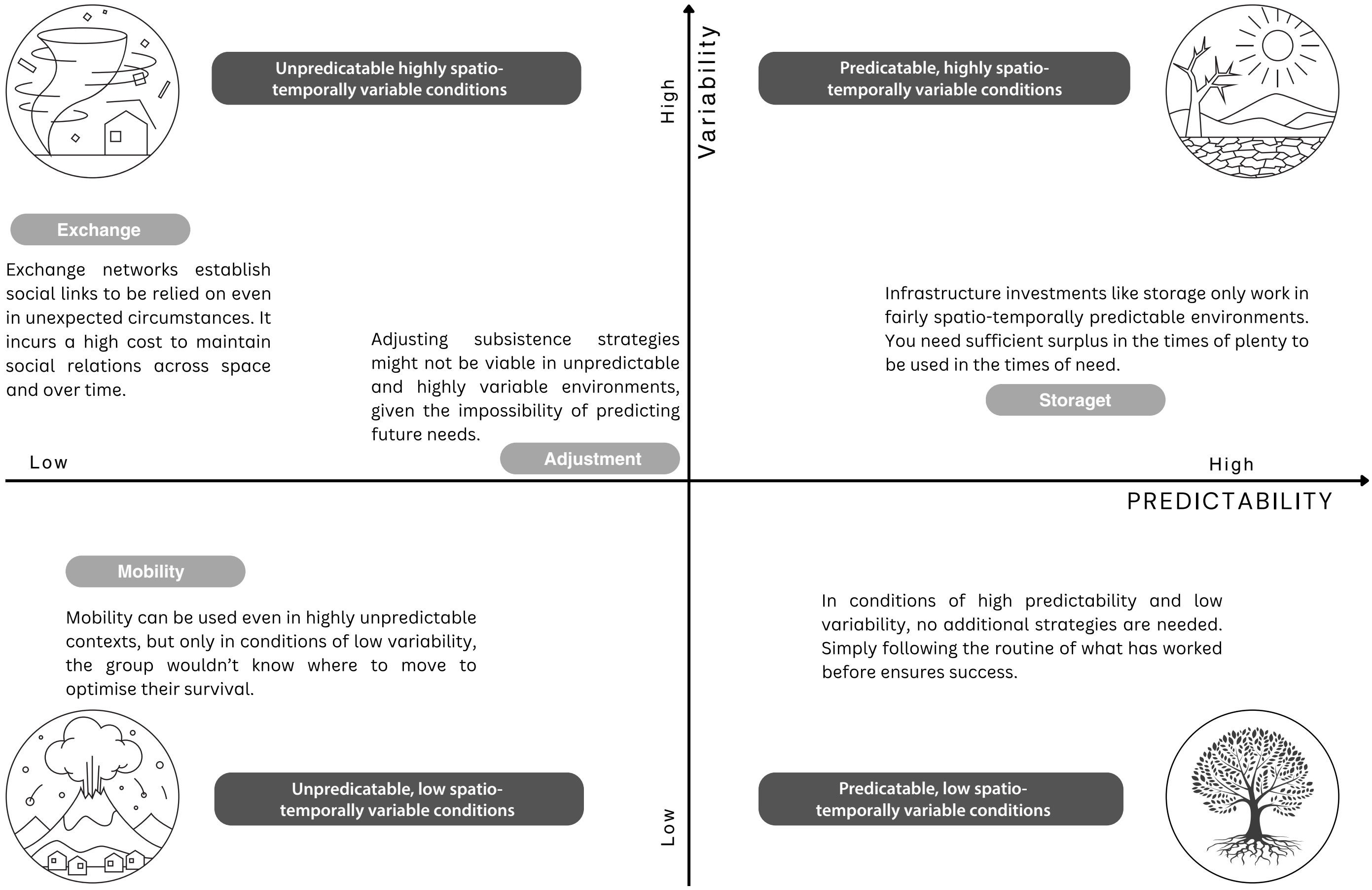

Fig. 1. Summary of the four buffering mechanisms. We place the buffers described by Halstead and O'Shea's BYE against axes of environmental variability and predictability.

In effectuating these behavioral adjustments, past and modern peoples were variably able to cope with different environmental stressors and resource shortfalls. Resilience, in our GoodBYE model, is tracked as the combined emerging property reflected in agent survival across a simulation run (effectiveness) and their ability to maintain or even increase their resource capital relative to the costs of enacting a given resilience strategy (efficiency).

RESULTS

For each scenario, the key output measures collected from the model are effectiveness, the total number of times an agent failed by running out of resources (fail_count), and efficiency, the number of times a resilience strategy was used by the agents (use_count), where each use implies cost. In addition we record run duration, the longevity of the population recorded as the duration of the simulation run (steps). Logically, the ideal resilience strategy would be both effective and efficient. That is, it should ensure that the agents do not run out of resources (effectiveness) and also that it incurs minimal cost, which it does not require agents to use the strategy repeatedly (efficiency).

We first conducted a sensitivity analysis of the model's environmental and population characteristics (see the Supplementary Materials). Second, we benchmarked the success of each resilience strategy against a relatively stable environmental condition to understand their baseline impact on the agent population. Last, we tested the strategies against different environmental conditions to evaluate their effectiveness and efficiency under a range of environmental scenarios. As originally hypothesized by Halstead and O'Shea (*27*), each resilience strategy affords different advantages and disadvantages under various spatial and temporal patterns of resource scarcity. Yet, the optimal mapping of these strategies onto different environmental stressors and shocks is far from intuitive.

Resilience strategies

The first series of experiments show the overall effectiveness and efficiency of each resilience strategy relative to no resilience strategy at all and the impact of the strength of each resilience strategy (on a one to five scale) under a relatively stable environment determined by low-frequency and low-amplitude resource fluctuation. Because utilization and failure rates are highly correlated with the duration of the run, we scaled the effectiveness and efficiency by the run duration and by the agent population size, such that the values show the effectiveness and efficiency of each resilience strategy per timestep and per agent (Fig. 2). Each plotted point represents the end state of one model run, and the separate clusters of results on the plot show the impact of each strategy's increases in strength on the effectiveness and efficiency rates.

Compared to no resilience strategy, all strategies are, on average, more effective, that is they reduce the number of times agents fail to acquire resources (fail_rate), although in some cases, when the strategy is weak, the differences are small. Increasing the strength of the resilience strategies increases the effectiveness even further.

The mobility strategy has the highest effectiveness at reducing the number of agent failures compared to the other strategies as agents are better able to locate remaining resources beyond their immediate area and thus avoid running out. The effectiveness of the strategy increases as the distance that each agent is able to travel to locate new resources increases (strategy_strength). The second most effective strategy is the infrastructural investment which allows agents to survive in resource-poor areas and times by relying on stored resources. However, the effectiveness is proportional to the strategy_strength parameter, which in this case determines how many time steps worth of resources are stored. Exchange similarly allows for greater survival at a time when local resources have been depleted, effectively by indirectly exploiting distant patches (those of the exchange partners) where resources are still available. Last, economic adjustment allows agents to extract a greater amount of resources by increasing the effort (intensification) or focusing on different types of resources (diversification). This strategy has a markedly less strong effect than the others. This is because once it is triggered, the available resources are already limited, meaning that more intensive investments in time or effort merely provide ever more marginal returns.

The second primary metric is the efficiency of the different resilience strategies, that is, the inverse of their utilization rate (use_rate). Because using a strategy comes at a metabolic cost, the method that is able to increase effectiveness (i.e., reduce the failure rate) while not needing to be used as often should be considered better overall. For most resilience strategies, there is an inverse relationship between the efficiency and the effectiveness such that the less a strategy is used (i.e., it is more efficient), the higher the failure rate is (i.e., less effective). For example, economic adjustment was used the least, but it also had the highest failure rate. While infrastructural investment had the highest utilization rate, it also resulted in some of the lowest failure rates. Mobility is an exception to this trend as failure rates were consistently low, and its utilization rate only decreased slightly as the strength of the strategy increased.

These baseline simulations, in a relatively stable environment characterized by low-frequency and low-amplitude resource fluctuations, benchmarks the effectiveness and efficiency of each strategy. However, as Halstead and O'Shea (*27*) theorized, the various strategies

Fig. 2. Effectiveness and efficiency of resilience strategies. Each point represents the end state of a run of the GoodBYE model, where color represents a different resilience strategy and point size represents the strength of the strategy. The *x*-axis use_rate shows the frequency a strategy had to be used because of resource shortfall (i.e., lower is higher efficiency), and the *y*-axis *fail_rate* shows the frequency that agents ran out of resources completely (i.e., lower is higher effectiveness).

and the combinations should function better against some types of environmental stressors and shocks than others. Thus, in the next section, we repeat the above experiments but modify the environmental conditions to test the efficiency and effectiveness of the resilience strategies against various forms of environmental change.

Effects of environmental change

We ran the model with a range of environmental scenarios designed to abstractly represent a wide range of environmental conditions of both cyclical stress (low amplitude versus high amplitude with low frequency versus high frequency) and sudden shocks with punctuated and persistent consequences on available resources. For these experiments, we fixed the strategy_strength to a moderate value.

We considered the following environmental comparisons:

1) Cyclical stress versus shock scenarios: Continuously cycling stress (Fig. 3, A and B) or punctuated environmental shock (Fig. 3C).

2) Punctuated versus persistent shock scenarios: Sudden environmental change characterized by gradual bettering of conditions or persistence of poor conditions for a period of time (Fig. 3C).

3) Tempered versus extreme conditions scenarios: Low or high amplitude of environmental change (Fig. 3, A or B).

4) Stable versus changing conditions scenarios: Low or high frequency of environmental change (Fig. 3, A versus B).

Overall, compared to continuous cyclical stress, sudden shocks typically had a more severe impact on the population in terms of effectiveness (higher rate of failure) and efficiency (higher rate of use) (Fig. 4). While agents were able to survive an event with a gradual recovery during an otherwise favorable environmental condition (i.e., punctuated shock during stable condition), a persistent event or any sudden shock during otherwise unfavorable conditions (i.e., high-frequency–high-amplitude conditions) caused a large decrease in effectiveness (increase in failure) and efficiency (increase in use). The persistent shock scenario, i.e., when low availability of resources caused by a sudden dramatic shock continued for some time before returning to the normal level, particularly when combined with high amplitude of the cyclical environmental changes created the least survivable conditions overall.

In contrast, cyclical stress in the environmental condition had a comparatively small impact on the agent population's well-being across all combinations of environmental parameters: high versus low amplitude and frequency. High-amplitude environmental swings, for both high- and low-frequency cycles, result in a slight decrease in survival for the population compared to low amplitude scenarios. While higher amplitude results in higher highs, this is offset by the "bad times," when resources are truly stressed, being even worse due to the much lower swings in resource availability. In contrast, the low-frequency scenarios where challenging swings lasted longer were the most costly in terms of resilience strategy use (affecting efficiency) and devastating for the population (affecting effectiveness).

Our results support the notion that each population is adapted to a particular range of environmental changes that they can sustain with their current behavior. Populations will collapse if the range of adaptations is exceeded, whether that is due to stress duration or amplitude. At that point, even a cyclical stress condition is nearly equivalent to a short-term shock as it triggers a sudden and catastrophic increase in agent failures. True shocks, particularly persistent shocks, have a severe impact on the population because such a "bad year" lasts much longer and does not allow for even incremental recoveries.

Among all resilience strategies, mobility is the best overall strategy across the wide variety of environmental change scenarios

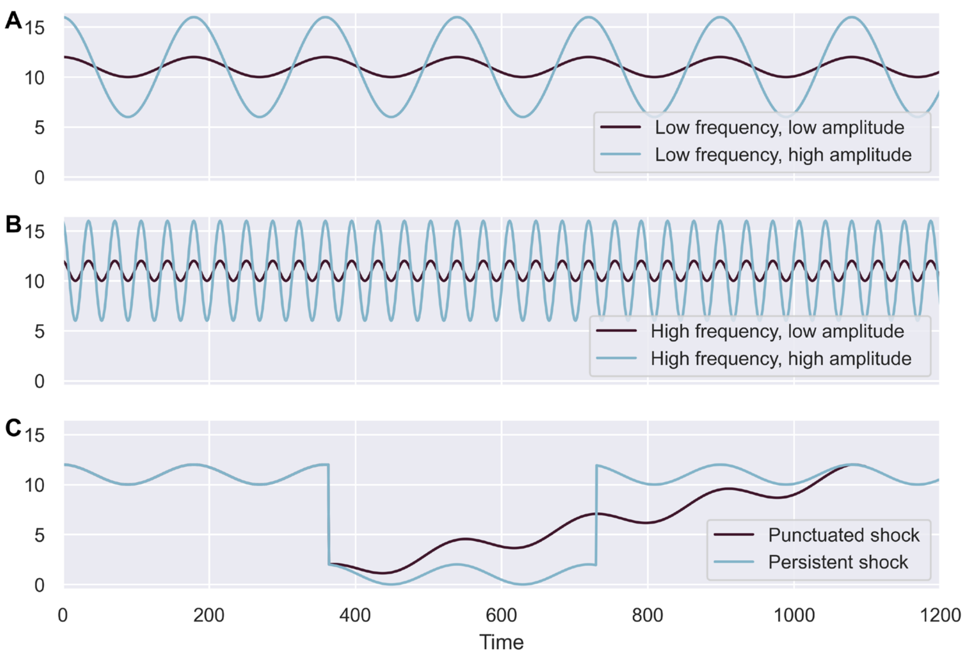

Fig. 3. Graphical representation of the six scenarios of environmental change. GoodBYE model's environmental change conditions include: (**A**) Low-frequency change with low versus high amplitude, (**B**) high-frequency change with low versus high amplitude, and (**C**) a punctuated shock that has gradual recovery versus a persistent shock with abrupt recovery. Not shown are two additional scenarios of a punctuated and a persistent shock occurring during a high-frequency, high-amplitude cyclical pattern.

Fig. 4. Impact of different resilience strategies across a range of environmental scenarios. Each point represents the end output values of a model run with color designating the resilience strategy available to the agents and shape designating the environmental scenario tested.

tested. It has the highest level of effectiveness, that is, substantially lowers failure rates compared to all other strategies, and has good efficiency, i.e., moderate cost. There are, however, environmental scenarios where mobility performs worse than some other strategies (infrastructural investment and exchange), namely, persistent shocks. Mobility is a strategy of improving access, in that it relies on finding sustainable areas of the landscape. However, during a persistent shock, the whole region is severely depleted of resources and so there are no favorable locations for the agents to move to.

Infrastructural investment is overall the most inefficient (i.e., expensive) resilience strategy but also the one that had the highest effectiveness (the lowest failure rates) in the harshest conditions of the persistent shock scenario and a good to moderate effectiveness for the stress scenarios. Thus, infrastructural investment is the best resilience strategy against the most severe types of shocks, but it is also the most costly with the highest utilization rate of all other strategies, almost three times the cost of other strategies, such as economic adjustment. Infrastructural investment would be particularly difficult to sustain in the face of poor conditions that persist longer than the capacity of this infrastructure (e.g., storage) as it relies on the availability of surplus resources during at least some periods to refill stores or rebuild flood defenses. This is reflected in infrastructural investment being less effective during the low-frequency–high-amplitude environmental stress because the longer durations of poorer conditions result in the agents going beyond the capacity of the infrastructure.

Exchange has a good to moderate effectiveness (low to moderate failure rate), similar to infrastructural investment for the stable cycling scenarios but somewhat worse during shock events. Exchange also has a moderate efficiency, similar to mobility across a range of environmental scenarios. In our model, exchange could be regarded as a combination of mobility and infrastructural investment. It is similar to mobility in that it relies on locating another area with higher resource availability, albeit indirectly via another agent. This results in exchange being a somewhat risky strategy because there may be no higher resource area to gain access to. For the agent, the mobility strategy has the advantage of continuing to be able to exploit the new area after moving, while for exchange, it is a single event that would then require continual reliance on that exchange partner until their own area recovers. On the other hand, exchange is similar to infrastructural investment in that it asks for a resource that is not "directly" available to the agent. In a way, the agent being asked to provide resources is the "store" for the asking agent. However, there is no cost of refilling that store as this is undertaken by the other agent, thus the higher efficiency.

Last, economic adjustment is overall the weakest strategy with the lowest effectiveness (highest failure rates) but also high efficiency (lowest cost). In our model (and in many real-world contexts), resilience strategies are only used when the agent is in distress, i.e., in a situation when the resource availability is already low. Economic adjustment enables the agent to generate more resources from the same baseline area (by diversifying the type of resources collected or intensifying their acquisition). However, in situations where the resource level is already low, attempting to harvest a larger amount from mostly depleted cells is unlikely to counteract the effects of the stress or shock. As the adage goes, it is "too little, too late", and populations that used this resilience strategy fared very poorly.

Overall, the frequency of agent resource failures increased markedly for sudden and severe environmental challenges, i.e., shock scenarios. Relative to no resilience, the strategies of economic adjustment, exchange, and mobility were more effective in reducing the failure rates by 14, 52, and 68%, respectively, at a low to moderate cost. For stress environmental conditions, mobility was the best strategy for lowering failure rates though that advantage disappeared under the more severe shock environmental scenarios. Infrastructural investment is the most inefficient (the highest cost) overall, yet the pay-off of that extra cost was worthwhile during the most severe shock conditions when it had the highest effectiveness—a 71% reduction in the failure rate.

DISCUSSION

The GoodBYE model demonstrates clear tradeoffs between different risk buffering strategies—there is no single strategy that is both highly effective at limiting harm and efficient, that is, incurring minimal cost. The example of infrastructural investment is a case in point. While it protects the population from the most severe of shocks, it also incurs substantial costs that need to be paid upfront and which may never be "cashed in" if the shock does not occur, a situation not modeled in GoodBYE but highly plausible in the real world. By the same token, intensifying or diversifying one's economic activities (economic adjustment) in times of crisis may be inexpensive, but it lowers the failure rate only slightly. Mobility seems to be the most successful strategy overall given its moderate cost and high effectiveness in a wide range of environmental crisis conditions. However, when a truly severe shock happens there is nowhere to go and mobility becomes much less effective.

In our representation of an ever-declining resource base, negative effects occur nonlinearly, with the population incurring large cumulative use costs during very short periods as they all attempt to acquire the few remaining resources. In this way, individuals acting locally result in broad and accelerating patterns of reduced effectiveness and efficiency, exemplifying the emergent dynamics of the system. This affects all strategies, e.g., exchange partners have no additional resources to offer and individuals have no extra resources to maintain their infrastructure, leading to rapid drops in efficiency as use increases and in effectiveness as strategies fail.

It is also worth noting that some of the adaptive strategies are more spatially constrained than others, e.g., investment in infrastructure such as storage or flood defenses is likely only effective if the group remains in close proximity to it. Contrast this with the reliance on social networks, which may be called upon even from long distances. These limitations add another axis of consideration for choosing the most appropriate risk buffering strategies. Similarly, the internal social dynamics, including endogenous stressors, likely have a substantial impact and should be explored further in future iterations of the model.

While the GoodBYE model is abstract in nature and not intended to be directly validated against a specific set of data, it produces testable predictions, which we illustrate through a series of archeological case studies and a comparative ethnographic analysis.

From model to real-world cases

Archeological proxies for human risk management, as framed here, are visible throughout the archeological record and the more recent past (*47*, *48*). During the Pleistocene with its high-amplitude and high-frequency climatic fluctuations (*49*), humans lived as foragers who primarily managed risk through mobility coupled, variously, with adjustments toward more diverse or more specialized economic strategies (*50*). From the Late Pleistocene onward, exchange began to emerge in the form of spatially extensive social networks that ostensibly served as safety nets in times of crisis (*45*, *51*, *52*). Beginning in the Late Pleistocene, and especially as climatic regimes shifted from the high-amplitude/high-frequency fluctuations of the Pleistocene to the low-frequency/low-amplitude conditions of the Holocene, infrastructure aimed at increasing resilience, such as storage, emerged as a major additional risk management measure especially as mobility rates decreased among some societies. Evidence of cache pits, fermenting, smoking, and roasting rises to archeological visibility. That said, there are also numerous cases of population collapse and disappearance that span both the Pleistocene (*53*–*55*) and the Holocene (*56*–*58*) and instances when substantial parts of otherwise sedentary populations with high investment in infrastructure and storage resort to mobility under pressures of the environment (*59*), often also associated with increased mortality and reduced well-being.

Cases documenting the breakdown of these resilience strategies (table S5) when sudden-onset punctuated shocks such as volcanic eruptions sufficiently disrupt ancient economies and social networks offer additional insights. One example here is the eruption of the Laacher See volcano ~13 thousand years before present (ka B.P.) and its downstream human impacts, which were at least partially contingent on social network failure (*60*, *61*). Similarly, foraging societies affected by the even larger mid-Holocene Mount Mazama (7.6 ka B.P.) or Kikai-Akahoya (7.3 ka B.P.) eruptions in North America and Japan, respectively, also appear to have met these challenges through mobility and reliance on social networks, possibly aided at this point by greater investments into storage technologies (*62*–*64*). In the context of these "natural experiments," the systematic differences in prior (risk/risk management) conditions, interventions (shocks), and outcomes reveal the efficacy of the different response strategies: Mobility was universally taken into use, as was exchange. The latter was not always reliable, however. For some populations, storage technologies appear to have made a vital difference. Clearest across these cases stands the diversity of available response strategies, deploying just one or few inevitably led to some form of long-term demographic impact [c.f. (*65*)].

In the case of sudden-onset events such as volcanic eruptions, the ultimate cause of the stress is evident, although the risk management strategies taken into use would be generic and draw on already established behavioral heuristics. Beyond the immediately destructive near-vent effects of volcanic eruptions, their downstream stressors on human societies would also normally be reduced temperatures, increased rainfall, or reductions to ecosystem services via ashfall. As a rare case where we can contrast the risk management strategies of two very different societies residing in identical ecosystems and in relation to slow-onset pressures, the fate of Inuit foragers and Norse settlers in Medieval Greenland offers powerful insights. Human presence in Greenland began with the Independence I culture around 2500 BCE, with the Thule migration around 1200 CE being the latest in a series of dispersal events onto the island (*66*, *67*). In the mid-980s, Viking settlers from Iceland arrived in southwest Greenland, bringing with them a package of resilience strategies rooted in the pasture-based farming of their homelands (*68*). In the 14th century CE, the Little Ice Age began, consistently depressing temperatures and increasing precipitation and storminess, exerting persistent pressure on these two different societal systems. Notably and concurrent with the late stages of the Little Ice Age, Norse settlements were eventually abandoned through outmigration (long-distance mobility), demographic collapse, or a combination of these (*68*, *69*). In contrast, the Thule culture relied on risk management strategies centered on shorter-range mobility—facilitated, in fact, by the more robust ice cover—combined with minor investments in storage and social networking. As a consequence, their population expanded at this time (*70*, *71*). As reflected in the Thule response, our model demonstrates that while persistent shocks with an unstable environmental background would be the most challenging environmental scenario, storage and mobility are both effective resilience strategies. While our model does not combine strategies, it is plausible that the combination of high and low efficiency strategies would be effective at balancing the trade-offs of each.

In contrast to the Thule, the Norse settlers initially responded by economic intensification combined with trade. Walrus ivory was their most precious commodity and when wider networks of supply and demand changed, this risk management option dried up (*72*). Instead, they turned to economic diversification to include more marine mammals in their diet, as indicated by isotopic evidence of shifting diet (*73*). At the same time, they appear to have invested ever greater energy into the intensification of existing agricultural practices, the costs of which were rising due to increasingly unfavorable conditions and the exhaustion of what limited arable land was available (*74*, *75*). As suggested by our model, this risk management strategy of economic adjustment and storage during a period of environmental stress is not an effective resilience strategy if the available resources are already at a low level or could be depleted quickly. In the case of the Norse, the inadequacy of this strategy was masked by increased trade with the mainland (exchange strategy), initially providing some response capacities. In the absence of trade as an additional resilience mechanism, however, returns became marginal and collapse ensued. The difference in demographic trajectories among the Norse and Thule, respectively, is also instructive. Even when trade was still in effect, Norse numbers were declining, while Thule populations appear to have enjoyed a steady increase during the same timeframe. Ultimately, their reliance on mobility as their major risk management strategy kept population density relatively low overall but ensured survival.

Integrating the insights offered by these diverse case studies with the results of models suggests that during the Pleistocene—generally corresponding to our scenario with high- frequency and high-amplitude resource variation—mobility and economic adjustment are the premier behavioral strategies used, supplemented by exchange. Notably, periods of population growth and successful expansion (e.g., the Aurignacian) tend to also be characterized by increased evidence for these strategies (*76*, *77*). As environmental regimes transition to the low-frequencies and low-amplitudes ones of the Holocene, infrastructure swiftly became integrated into the behavioral repertoire and eventually predominated among those societies characterized by the greatest population increases—broadly the more complex and hierarchical societies that emerged in the course of the Holocene partly because infrastructure developments were expanded and repurposed [(*36*), although see (*78*)]. By this token, our model aligns with the long arc of human history in which we see ever more intensive investments into infrastructure such as storage structures and irrigation systems that correlate with population increase and, incidentally, environmental transformation and degradation [e.g., (*79*)]. The flipside of focused infrastructure investments and economic adjustment in the form of intensification are that populations became vulnerable to stressors that fall outside of the frequency and amplitude ranges on which these behaviors were initially calibrated. As is increasingly appreciated, many periods of culture change in the Holocene did occur around these "moments of crisis" (*80*) when marked and archeologically visible behavioral adjustments were necessary or when impacts due to a lack or lag in adjustment became evident.

Cross-cultural analysis

Beyond archeological case studies, the GoodBYE model finds further support in cross-cultural analysis. The results of the model show that the trade-offs between different resilience strategies are substantial enough that none is optimal under all circumstances. We would therefore predict that different communities living in different environmental regimes and with some level of resource risk should engage in a variety of resilience strategies. Ethnographic evidence supports this notion. Across several datasets collected in D-Place (*81*, *82*) that represent hundreds of human groups, none of the four large classes of resilience strategies—infrastructure investment, mobility, trade, or economic adjustmen—is uniformly or even systematically adopted by all communities (table S4). For example, the proportion of communities recorded in datasets such as the standard cross-cultural sample (*83*) that have paid the upfront cost to develop risk-buffering infrastructure, such as a complex storage solution, intensive irrigation system, or sophisticated forms of water transport is around 15% despite the high effectiveness of these approaches in the face of severe shocks suggested by our model. This indicates that the high cost identified in the model is, in fact, a notable deterrent to wider adoption.

The model results also showed a strong indication that adjustment of the subsistence economy, while carrying little cost, displays low efficiency in terms of preventing the negative consequences of shocks and stresses. This finding is also supported by ethnographic evidence. For example, Dirks (*84*) evaluated the widely held belief that hunting and gathering provide more flexibility in the subsistence strategy, enabling foraging communities to easily switch to a source of calories that is not currently under stress, while, in contrast, among agricultural societies, a failure of one crop is synonymous with famine and starvation. While this proposition sounds plausible at face value, a comparative analysis of groups engaged in foraging, agricultural, and mixed subsistence strategies found no clear relationships between reliance on foraging and occurrence, contingency, or persistence of periods of starvation (table S4). The ability to diversify the food base alone does not seem to confer a substantial advantage for overall group resilience when facing environmental downturns or shocks. Note that the way economic adjustment is modeled in GoodBYE differs from expected seasonal shifts in which foods are acquired [i.e., fall-back foods (*85*)].

The prevalence of the different strategies, such as agricultural and non-agricultural intensification or introduction of new crops and farm animals, which were identified as possible proxies for economic adjustment, varies between 16 and 33% among communities—a clear sign that simple correlations are unlikely to capture the diversity and complexity of human response strategies to shocks and stresses. Similarly, the evidence for upfront investments in fostering social links to those one may call upon in times of need is far from universal among ethnographically recorded communities. On the one hand, most recorded communities engage in some form of exchange with each other, such as market or gift exchange, but on the other, there are no known examples of extralocal communities such as tribes or districts joining forces to distribute food in times of scarcity. This behavior at a level of a village or a band has been recorded in only 37 of the 164 groups (table S5).

While these indicative case studies and cross-cultural examples provide some tentative support to the results, a systematic analysis of ethnographic, historical, and archeological evidence for shocks and stresses as well as the resilience strategies implemented is needed to gain a robust understanding of the tradeoffs involved and the optimal matching between different risk types and resilience strategies [c.f. (*86*, *87*)].

Looking ahead

In light of the rapidly changing climate and ever more frequent extreme climate events (*88*), fostering resilience today is a major priority in research and policy. The model presented here was developed with traditional, small-scale societies in mind, yet the strategies outlined in the GoodBYE model can be generalized beyond this context as they represent fundamental coping strategies that have been observed at individual, group, and whole-society scales (*47*). Similarly, approaches in disaster risk reduction stress that access to resources is vital for building resilience (*28*). The United Nation (UN) guidelines (*89*) for resilience building identify social networks, diversification of incomes, or technical/infrastructural potential as societal capacities that increase resilience. These are encompassed in the GoodBYE model as (i) exchange, (ii) economic adjustment, and (iii) infrastructural investment strategies, respectively. Notably, the UN guidelines do not mention mobility despite it being recognized as a common response to environmental stressors (*90*) and one that is clearly identified by our model as a robust behavioral response to crisis. Past human groups used all four of these strategies in parallel and in variable combinations against a wide range of stressors. The differential success rates of these natural experiments provide a unique source of comparative information about the efficacy of these broad resilience strategies under different circumstances. Better understanding of the underlying dynamics can help us to anticipate the impacts of future climate and ecological changes on human societies and potentially to give us time to implement the optimal policy changes required to promote more resilient societies (*13*, *91*, *92*).

The past offers a laboratory in which the behavioral mechanisms that lead to resilience can be studied. Formal models allow us to move from documenting proxy data to understanding the underlying mechanisms. The model presented here is informed by archeological and contemporary observations on how human communities mitigate environmental risk. The insights gained about which mitigation measures are most effective and efficient under different scenarios align well with key case studies. The formal nature of our model allows us to move beyond these cases, however, as it provides insights into the general resilience mechanisms that are also of relevance to the contemporary world (*93*).

Two insights in particular are worth highlighting. First, mobility serves as not only a moderately costly but also efficient risk mitigation strategy in all scenarios. Today, few communities practice truly mobile lifestyles, and domestic and national borders often make movement difficult. Our models suggest, however, that under conditions of severe and prolonged environmental pressure, people will most likely move. Under realistic scenarios of future climate change, the niche space for agriculture will shift markedly (*94*, *95*), and existing systems of behavioral adjustment are said to come under pressure (*96*, *97*) especially given the projected changes in vital ecosystem services (*98*) and the concomitant increase of extreme events (*88*, *99*). Considering how climate change affects communities, such that repeated large-scale migrations may become a common form of adaptation, understanding the conditions under which people resort to these major behavioral adjustments must be a priority lest humanity at large resorts to a "hunter-gatherer future" (*100*) where mobility again dominates as the only truly viable response to environmental stress.

Second, negative consequences are likely to emerge as a consequence of risk mitigation failure. In our models, many resilience strategies perform poorly under a range of scenarios. The mapping of which strategy has the best chance of working for each particular community and their environmental context is paramount as we show that there is no "silver bullet" solution that will prove optimal in all circumstances. While we do not model conflict specifically, it has been suggested that it is a direct corollary of these mitigation failures [(*27, 28, 101*), although see (*29*)]. Building resilience by promoting nonviolent risk mitigation measures will contribute to just and safe conditions for human life.

The foundational behavioral response strategies of mobility, infrastructural investment, exchange, and economic adjustment transpose seamlessly to the present [see for example (*89*)], and we suggest that agent-based modeling can provide a major technique to deliver future-directed insights into which specific mitigation measures and resilience strategies best match each form of environmental disturbance. In particular, this approach allows us to trace how individual adaptive responses collectively shape system-level dynamics, revealing the emergent properties of socio-ecological systems in times of crisis. As much as they offer insights about the past, these models allow us to project societal trajectories into the future. In this way, we can complement the use of paleoenvironmental data to support the development of testable scenarios of climate change with "paleosocietal" data to construct attendant societal response strategies (*102*).

MATERIALS AND METHODS

Model description

The GoodBYE model reaches directly to the original conceptualisation of BYE by Halstead and O'Shea (*27*), which focused on risk management through behavioral response strategies to external stressors. The model consists of a stable population of individual agents representing a local population and an environment representing spatially distributed heterogeneous resources exploited by the agents for survival. Hence, they can be considered as one socio-ecological system. The spatial and temporal resolution is relative but may be idealized as a unit of time necessary to exhaust the resources of one spatial unit. See the Supplementary Materials for a full description of the model including the list of state variables (table S1).

We use the GoodBYE model to investigate the interaction between environmental change and agents' ability to absorb that change by asking: Which resilience strategy is most successful for each type of environmental crisis? We vary the conditions of each environmental scenario by setting parameters for the intensity (amplitude), prevalence (frequency), and distribution of environmental change (stress or shock) while testing each of the behavioral strategies (mobility, infrastructure, exchange, and adjustment) individually during separate runs of the model. GoodBYE is designed to make the costs of each strategy equivalent, although the timing of when those costs are paid by the agents may not be, such that the aggregated result of agent behavior is the key comparison between the strategies. All scenarios run until agents deplete the resources to the extent that the average resource patch has less than the agent's daily metabolic cost. This allows us to assess the suitability of each strategy in response to a given stressor in a consistent and comparable way. The main outputs of each model run are effectiveness—the count of how many times an agent failed to acquire adequate resources (fail_count) and efficiency—the total number of times a resilience strategy was used (use_count), and the duration of the run in terms of number of time steps (run_duration), which is used to scale the other two measures. Every parameter combination is run 20 times to account for model stochasticity.

Environmental change

Research into long- and short-term climate cycles have demonstrated that a complex combination of factors, such as orbital characteristics (i.e., Milankovitch cycles) and feedbacks between ice sheets and ocean currents (e.g., Dansgaard-Oeschger events) have affected the pattern of global climate oscillations. Overall, this led to a pattern of high-amplitude–high frequency variations in interannual climate during the Glacials such as the Pleistocene and low amplitude–low frequency during the Holocene Interglacial (*49*, *103*). Similarly, studies of climatic impacts of major volcanic eruptions have shown a systematic pattern of rapid decline and gradual recovery as ejecta affect the Earth's heat balance, often leading to abrupt cooling at various spatial scales (*104*, *105*); other types of environmental perturbations (i.e., boqnd events and associated cooling and drying) occur over intermediate timescales. To abstractly represent this broad range of environmental change scenarios, we model the environment as a temporal process affecting the base level of resources (environmental richness) as a function of frequency, amplitude, and shift from the baseline conditions (see Supplementary Text, section 1.2.2, and fig. S1). The environmental change is thus modeled as a combination of these three factors resulting in eight types of environmental stress or shock crises (Table 1 and Fig. 3).

The spatial variability is represented by heterogeneously distributed resources using a homogeneous Poisson and Matérn clustering process (*106*) and with a richness gradient spanning from north to south. The total amount of resources distributed across the landscape at the start of the runs is always the same despite the different environmental scenarios. Agents exploiting the resources remove them permanently thus gradually decreasing the total amount of resources present in the environment. Harvesting a cell during an environmental downturn will degrade the cell more because the agent's constant harvest rate takes a greater proportion of the patch's remaining capacity. This puts the agents in an increasingly precarious position and ensures that resilience strategies are needed more and more often as the run progresses. This process is the same for all resilience strategies tested.

Agent strategies

At every step, agents secure their subsistence through local mobility (to neighboring cells) using an imperfect hill climbing algorithm (*107*) and resource exploitation, i.e., harvesting and then consuming resources. If an agent's resource level falls below a defined threshold (their daily metabolic needs for most strategies or a depleted infrastructure level for infrastructure), i.e., they enter into a bad year, then this triggers one of the four resilience strategies: mobility,

Table 1. Environmental scenarios The first four scenarios are consistent stress with variable frequency and amplitude of the environment. The second four simulate rapid, catastrophic environmental shocks but with different recovery characteristics. These occur with either a stable (low frequency–low amplitude) or unstable (high frequency–high amplitude) background condition.

Scenario	Frequency	Amplitude	Sudden event
Low frequency–low amplitude	2	1	
High frequency–low amplitude	10	1	
Low frequency–high amplitude	2	5	
High frequency–high amplitude	10	5	
Low stress environment, punctuated shock	2	1	Rapid drop, gradual recovery
Low stress environment, persistent shock	2	1	Rapid drop, rapid recovery
High stress environment, punctuated shock	10	5	Rapid drop, gradual recovery
High stress environment, persistent shock	10	5	Rapid drop, rapid recovery

adjustment, infrastructure, or exchange. Using the mechanisms comes at a set cost added to their metabolic needs (the same for all strategies). If an agent's resource level falls below zero, then they die and a new agent is created at a random location. The specifics of each resilience strategy and the effect of the strategy_strength parameter are:

1) Mobility: Agent moves to the cell with the highest resource level within a specified radius determined by the strategy_strength parameter. This represents medium-to-long distance relocation as opposed to local mobility. Cost represents the additional energetic cost of relocation and is paid at the time of the movement.

2) Economic adjustment: Agent is able to harvest an increased amount of resources from their local cell, although this is limited by availability. The percent increase in yield is determined by the strategy_strength parameter. The economic adjustment strategy may represent several types of adaptations that enable more efficient or higher volume gains at the time of harvest, e.g., intensification of resource harvest or diversification of the resources being harvested. Cost represents the effort of harvesting additional resources and is paid at the time of harvest.

3) Exchange: Agent requests resources from another agent and then selects the agent with the greatest amount of resources on their cell irrespective of distance. This represents resilience strategies dependent on social networks, such as calling on extended kin networks for help or community-level social welfare norms. The size of the social pool that can be asked for help is determined by the strategy_strength parameter. Cost represents the effort of contacting the exchange partner and is paid at the time of the request rather than in establishing/maintaining the network in advance.

4) Infrastructure: Agent stores extra harvested resources up to a limit, determined by the strategy_strength parameter, and can access them in the event of a resource shortfall. This represents "futureproofing" strategies where upfront investments are made before a crisis, e.g., storage facilities, irrigation, flood defenses, etc. Cost represents the initial investment in the infrastructure and is paid in advance, i.e., when the resources are initially stored.

Initialization and scheduling

Agents are initialized with the maximum resource level and one of four resilience strategies, i.e., in each run, all agents deploy one strategy and agents do not switch within the duration of one run. The high-level overview of model scheduling is given in Fig. 5. Agents forage in the closest neighborhood through local mobility modeled as an imperfect hill climber. They harvest the resources up to the

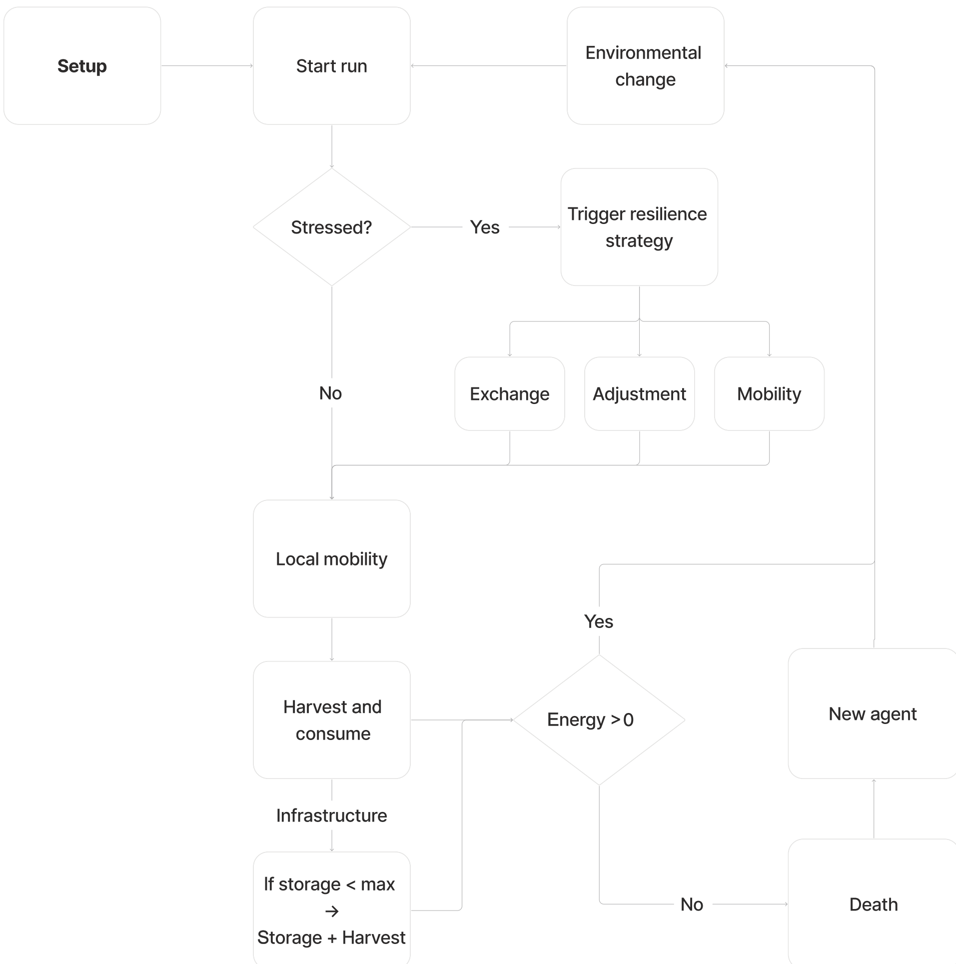

Fig. 5. Model schedule overview. Flow diagram of the main go loop of the simulation showing the sequence of procedures (rounded cells) and checks (diamonds) the model follows with each time step.

level available in the grid cell and their maximum foraging capacity. Agents check whether their resource level has fallen beneath the survivability level, that is, the amount of resources necessary to survive for one time step. If so, they enter into the bad year or "stressed" state, which triggers one of the three resilience strategies. In the infrastructure scenario, a slightly different definition of stress is used in that the investment is made in advance, i.e., before the crisis, and the state of bad year is triggered if the stored resources fall below the Infrastructure maximum. Using any one of the resilience strategies incurs a set cost levied in resources, which is the same for all strategies. Agents who nevertheless fail to secure enough resources die. This triggers the creation of a new agent, who is initialized in a random cell on the landscape, maintaining a constant population size and pressure on the resource base. Data, including the number of agents who triggered a bad year resilience strategy (use_count) and the number of deaths (fail_count), are collected at each time step. A detailed and formalized model description using the Overview, Design concepts, and Details (ODD) protocol (*108*, *109*), is available in the SI.

Supplementary Materials

The PDF file includes:
Supplementary Text
Figs. S1 to S8
Tables S1 to S3
Legends for tables S4 and S5
References

Other Supplementary Material for this manuscript includes the following:
Tables S4 and S5

REFERENCES AND NOTES

1. C. S. Holling, Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.* **4**, 1–23 (1973).
2. C. Folke, Resilience: The emergence of a perspective for social–ecological systems analyses. *Glob. Environ. Chang.* **16**, 253–267 (2006).
3. E. Ostrom, A general framework for analyzing sustainability of social-ecological systems. *Science* **325**, 419–422 (2009).
4. B. Walker, C. S. Holling, S. R. Carpenter, A. P. Kinzig, Resilience, adaptability and transformability in social-ecological systems. *Ecol. Soc.* **9**, 5 (2004).
5. C. Folke, S. R. Carpenter, B. Walker, M. Scheffer, T. Chapin, J. Rockström, Resilience thinking: Integrating resilience, adaptability and transformability. *Ecol. Soc.* **15**, art20 (2010).
6. D. G. Nimmo, R. Mac Nally, S. C. Cunningham, A. Haslem, A. F. Bennett, Vive la résistance: Reviving resistance for 21st century conservation. *Trends Ecol. Evol.* **30**, 516–523 (2015).
7. P. Riris, J. G. De Souza, Formal tests for resistance-resilience in archaeological time series. *Front. Ecol. Evol.* **9**, 740629 (2021).
8. J. Henrich, Human cooperation: The Hunter-Gatherer puzzle. *Curr. Biol.* **28**, R1143–R1145 (2018).
9. J. Brewer, F. Riede, Cultural heritage and climate adaptation: A cultural evolutionary perspective for the Anthropocene. *World Archaeol.* **50**, 554–569 (2018).
10. E. Ostrom, *Understanding Institutional Diversity* (Princeton Univ. Press, 2005); https://digitalcommons.usu.edu/unf_research/54).
11. C. Lyon, Place systems and social resilience: A framework for understanding place in social adaptation, resilience, and transformation. *Soc. Nat. Resour.* **27**, 1009–1023 (2014).
12. P. Sakdapolrak, H. Sterly, M. Borderon, S. Bunchuay-Peth, S. Naruchaikusol, K. Ober, L. Porst, T. Rockenbauch, Translocal social resilience dimensions of migration as adaptation to environmental change. *Proc. Natl. Acad. Sci. U.S.A.* **121**, e2206185120 (2024).
13. A. Burke, M. C. Peros, C. D. Wren, F. S. R. Pausata, J. Riel-Salvatore, O. Moine, A. de Vernal, M. Kageyama, S. Boisard, The archaeology of climate change: The case for cultural diversity. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2108537118 (2021).
14. M. J. Jacobson, Archaeological evidence for community resilience and sustainability: A bibliometric and quantitative review. *Sustainability* **14**, 16591 (2022).
15. M. E. Smith, How can research on past urban adaptations be made useful for sustainability science? *Glob. Sustain.* **6**, e4 (2023). https://doi.org/10.1017/sus.2023.2.
16. M. Løvschal, Retranslating resilience theory in archaeology. *Ann. Rev. Anthropol.* **51**, 195–211 (2022).
17. M. Bradtmöller, S. Grimm, J. Riel-Salvatore, Resilience theory in archaeological practice—An annotated review. *Quat. Int.* **446**, 3–16 (2017).
18. C. Lancelotti, X. Rubio-Campillo, M. Salpeteur, A. L. Balbo, M. Madella, "Testing the resilience of agro-pastoralists communities in arid margins through ABM" in *Advances in Computational Social Science and Social Simulation Barcelona* (Universitat Autònoma de Barcelona, 2014; https://ddd.uab.cat/record/128053).
19. D. F. Lorenz, The diversity of resilience: Contributions from a social science perspective. *Nat. Hazards* **67**, 7–24 (2013).
20. R. E. Barrios, Resilience: A commentary from the vantage point of anthropology. *Ann. Anthropol. Pract.* **40**, 28–38 (2016).
21. D. E. Alexander, Resilience and disaster risk reduction: An etymological journey. *Nat. Hazards Earth Syst. Sci.* **13**, 2707–2716 (2013).
22. K. Chmutina, G. Lizarralde, J. Von Meding, L. Bosher, Standardised indicators for "resilient cities": The folly of devising a technical solution to a political problem. *Int. J. Disaster Resil. Built Environ.* **14**, 514–535 (2023).
23. W. N. Adger, T. P. Hughes, C. Folke, S. R. Carpenter, J. Rockström, Social-ecological resilience to coastal disasters. *Science* **309**, 1036–1039 (2005).
24. D. Kim, S.-K. Song, Measuring changes in urban functional capacity for climate resilience: Perspectives from Korea. *Futures* **102**, 89–103 (2018).
25. K. Van Meerbeek, T. Jucker, J. Svenning, Unifying the concepts of stability and resilience in ecology. *J. Ecol.* **109**, 3114–3132 (2021).
26. C. L. Redman, Resilience theory in archaeology. *Am. Anthropol.* **107**, 70–77 (2005).
27. P. Halstead, J. O'Shea, *Bad Year Economics: Cultural Responses to Risk and Uncertainty* (Cambridge Univ. Press, 1989).
28. P. Blaikie, T. Cannon, I. Davis, B. Wisner, *At Risk: Natural Hazards*, *People's Vulnerability and Disasters* (Routledge, ed. 2, 2014).
29. O. Soffer, Storage, sedentism and the Eurasian Palaeolithic record. *Antiquity* **63**, 719–732 (1989).
30. T. Ulus, R. Ellenblum, How long and how strong must a climatic anomaly be in order to evoke a social transformation? Historical and contemporaneous case studies. *Humanit. Soc. Sci. Commun.* **8**, 252 (2021).
31. J. E. Yellen, Long term hunter-gatherer adaptation to desert environments: A biogeographical perspective. *World Archaeol.* **8**, 262–274 (1977).
32. S. Van Der Leeuw, Resilience: The importance of the long term. *Archéologie société et environnement* **2**, 10.21494/ISTE.OP.2021.0643 (2021).
33. T. A. Kohler, S. Cole, S. Ciupe, Population and warfare: A test of the Turchin model in Puebloan societies, in *Pattern and Process in Cultural Evolution*, S. Shennan, Ed. (University of California Press, Berkeley, 2009), pp. 277–295.
34. P. Turchin, A. V. Korotayev, Population dynamics and internal warfare: A reconsideration. *Soc. Evol. Hist.* **5**, 121–158 (2006).
35. W. C. Carleton, M. Collard, M. Stewart, H. S. Groucutt, A song of neither ice nor fire: Temperature extremes had no impact on violent conflict among european societies during the 2nd millennium CE. *Front. Earth Sci.* **9**, 769107 (2021).
36. R. L. Kelly, *The Lifeways of Hunter-Gatherers: The Foraging Spectrum* (Cambridge Univ. Press, ed. 2, 2013).
37. D. W. Anthony, Migration in archeology: The baby and the bathwater. *Am. Anthropol.* **92**, 895–914 (1990).
38. B. Winterhalder, E. A. Smith, Analyzing adaptive strategies: Human behavioral ecology at twenty-five. *Evol. Anthropol. News Issues Rev.* **9**, 51–72 (2000).
39. B. F. Codding, D. W. Bird, Behavioral ecology and the future of archaeological science. *J. Archaeol. Sci.* **56**, 9–20 (2015).
40. D. J. Kennett, T. P. Beach, Archeological and environmental lessons for the Anthropocene from the Classic Maya collapse. *Anthropocene* **4**, 88–100 (2013).
41. A. Testart, R. G. Forbis, B. Hayden, T. Ingold, S. M. Perlman, D. L. Pokotylo, P. Rowley-Conwy, D. E. Stuart, The significance of food storage among hunter-gatherers: Residence patterns, population densities, and social inequalities [and comments and reply]. *Curr. Anthropol.* **23**, 523–537 (1982).
42. S. Colledge, J. Conolly, B. Finlayson, I. Kuijt, New insights on plant domestication, production intensification, and food storage: The archaeobotanical evidence from PPNA Dhra'. *Levant* **50**, 14–31 (2018).
43. E. Galili, J. Benjamin, V. Eshed, B. Rosen, J. McCarthy, L. K. Horwitz, A submerged 7000-year-old village and seawall demonstrate earliest known coastal defence against sea-level rise. *PLOS ONE* **14**, e0222560 (2019).
44. P. D. Nunn, In anticipation of extirpation. *Environ. Humanit.* **12**, 113–131 (2020).
45. R. Whallon, Social networks and information: Non-"utilitarian" mobility among hunter-gatherers. *J. Anthropol. Archaeol.* **25**, 259–270 (2006).
46. B. Fitzhugh, S. C. Phillips, E. Gjesfjeld, "Modeling Variability in Hunter-Gatherer Information Networks: An Archaeological Case Study from the Kuril Islands" in

Information and Its Role in Hunter-Gatherer Bands, R. Whallon, W. A. Lovis, R. K. Hitchcock, Eds. (UCLA/Cotsen Institute of Archaeology Press, 2011), pp. 85–115.
47. W. Leal Filho, N. R. Matandirotya, J. M. Lütz, E. A. Alemu, F. Q. Brearley, A. A. Baidoo, A. Kateka, G. M. Ogendi, G. B. Adane, N. Emiru, R. A. Mbih, Impacts of climate change to African indigenous communities and examples of adaptation responses. *Nat. Commun.* **12**, 6224 (2021).
48. S. Biagetti, D. Zurro, J. Alcaina-Mateos, E. Bortolini, M. Madella, Quantitative Analysis of Drought Management Strategies across Ethnographically-Researched African Societies: A Pilot Study. *Landarzt* **10**, 1062 (2021).
49. J. J. Lowe, M. Walker, *Reconstructing Quaternary Environments* (Routledge, ed. 3, 2014).
50. W. J. Burroughs, *Climate Change in Prehistory: The End of the Reign of Chaos* (Cambridge Univ. Press, 2005).
51. M. Vanhaeren, F. d'Errico, Aurignacian ethno-linguistic geography of Europe revealed by personal ornaments. *J. Archaeol. Sci.* **33**, 1105–1128 (2006).
52. J. Baker, S. Rigaud, D. Pereira, L. A. Courtenay, F. d'Errico, Evidence from personal ornaments suggest nine distinct cultural groups between 34,000 and 24,000 years ago in Europe. *Nat. Hum. Behav.* **8**, 431–444 (2024).
53. E. Eller, Population extinction and recolonization in human demographic history. *Math. Biosci.* **177-178**, 1–10 (2002).
54. E. Eller, J. Hawks, J. H. Relethford, Local extinction and recolonization, species effective population size, and modern human origins. *Hum. Biol.* **81**, 805–824 (2009).
55. J. B. Pedersen, J. J. Assmann, S. Normand, D. N. Karger, F. Riede, Climate niche modeling reveals the fate of pioneering Late Pleistocene populations in Northern Europe. *Curr. Anthropol.* **64**, 599–608 (2023).
56. D. H. Holly, When foragers fail: In the eastern Subarctic, for example, in *Hunter-gatherer archaeology as historical process*, K.E Sassaman, D. H. Holly Jr, Eds. (The Univ. of Arizona Press, 2011), pp. 79–92.
57. D. Holly, C. Wolff, S. H. Hull, "The struggle was real: On the end of the archaic on the island of Newfoundland and Labrador" in *The Far Northeast*, K. R. Holyoke, M. G. Hrynick, Eds. (Univ. of Ottawa Press, 2021), pp. 23–48; doi.org/10.1515/9780776629667-004.
58. C. N. Keckler, "Catastrophic mortality in simulations of forager age-at-death: Where did all the humans go?" in *Integrating Archaeological Demography: Multidisciplinary Approaches to Prehistoric Populations. Center for Archaeological Investigations, Occasional Papers* No. 24, R. R. Paine, Ed. (Center for Archaeological Investigations, 1997), pp. 205–228.
59. J. Holopainen, S. Helama, Little Ice Age Farming in Finland: Preindustrial Agriculture on the Edge of the Grim Reaper's Scythe. *Hum. Ecol.* **37**, 213–225 (2009).
60. F. Riede, Eruptions and ruptures—A social network perspective on vulnerability and impact of the Laacher See eruption (c. 13,000 BP) on Late Glacial hunter-gatherers in northern Europe. *Archaeol. Rev. Camb.* **29**, 67–102 (2014).
61. F. Riede, *Splendid Isolation: The Eruption of the Laacher See Volcano and Southern Scandinavian Late Glacial Hunter-Gatherers* (Aarhus Universitetsforlag, 2017).
62. J. Uchiyama, M. Kuwahata, Y. Kowaki, N. Kamijō, J. Talipova, K. Gibbs, P. D. Jordan, S. Isaksson, Disaster, survival and recovery: The resettlement of Tanegashima Island following the Kikai-Akahoya 'super-eruption', 7.3ka cal BP. *Antiquity* **97**, 557–575 (2023).
63. G. A. Oetelaar, A. B. Beaudoin, Evidence of cultural responses to the impact of the Mazama ash fall from deeply stratified archaeological sites in southern Alberta, Canada. *Quat. Int.* **394**, 17–36 (2016).
64. F. Riede, G. Oetelaar, R. VanderHoek, "From Crisis to Collapse in Hunter-Gatherer Societies" in *Crisis to Collapse: The Archaeology of Social Breakdown*, T. Cunningham, J. Driessen, Eds. (Presses universitaires de Louvain, 2017), p. 19.
65. F. Riede, Towards a science of past disasters. *Nat. Hazards* **71**, 335–362 (2014).
66. M. Friesen, "Pan-Arctic population movements: The Early Paleo-Inuit and Thule Inuit migrations" in *The Oxford Handbook of the Prehistoric Arctic*, M. Friesen, O. Mason, Eds. (Oxford Univ. Press, 2016); https://doi.org/10.1093/oxfordhb/9780199766956.013.40.
67. H.-C. Gulløv, "Inuit-European interactions in Greenland" in *The Oxford Handbook of the Prehistoric Arctic*, M. Friesen, O. Mason, Eds. (Oxford Univ. Press, 2016), p. 897–914; https://doi.org/10.1093/oxfordhb/9780199766956.013.44.
68. J. Arneborg, "The Norse Settlements in Greenland" in *The Viking World*, S. Brink, N. Price, Eds. (Routledge, 2008; https://abdn.elsevierpure.com/en/publications/the-viking-world-2), pp. 588–597.
69. N. Lynnerup, Endperiod demographics of the Greenland Norse. *J. N. Atl.* **7**, 18–24 (2014).
70. R. McGhee, "The population size and temporal duration of Thule culture in Arctic Canada" in *On the Track of the Thule Culture from Bering Strait to East Greenland. Proceedings of the SILA Conference "The Thule Culture - New Perspectives in Inuit Prehistory", Copenhagen, Oct. 26th–28th, 2006. Papers in Honour of Hans Christian Gulløv*, B. Grønnow, Ed. (Copenhagen National Museum, 2009), pp. 75–91.
71. B. Grønnow, H. C. Gulløv, B. H. Jakobsen, A. B. Gotfredsen, L. H. Kauffmann, A. Kroon, J. B. T. Pedersen, M. Sørensen, At the edge: High Arctic Walrus hunters during the Little Ice Age. *Antiquity* **85**, 960–977 (2011).
72. K. M. Frei, A. N. Coutu, K. Smiarowski, R. Harrison, C. K. Madsen, J. Arneborg, R. Frei, G. Guðmundsson, S. M. Sindbæk, J. Woollett, S. Hartman, M. Hicks, T. H. McGovern, Was it for walrus? Viking Age settlement and medieval walrus ivory trade in Iceland and Greenland. *World Archaeol.* **47**, 439–466 (2015).
73. D. E. Nelson, J. Heinemeier, N. Lynnerup, Á. E. Sveinbjörnsdóttir, J. Arneborg, An isotopic analysis of the diet of the Greenland Norse. *J. N. Atl.* **3**, 93–118 (2012).
74. A. J. Dugmore, T. H. McGovern, O. Vésteinsson, J. Arneborg, R. Streeter, C. Keller, Cultural adaptation, compounding vulnerabilities and conjunctures in Norse Greenland. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 3658–3663 (2012).
75. R. Jackson, J. Arneborg, A. Dugmore, C. Madsen, T. McGovern, K. Smiarowski, R. Streeter, Disequilibrium, adaptation, and the Norse settlement of Greenland. *Hum. Ecol.* **46**, 665–684 (2018).
76. W. Davies, A very model of a modern human industry: New perspectives on the origins and spread of the Aurignacian in Europe. *Proc. Prehist. Soc.* **67**, 195–217 (2001).
77. R. L. Kelly, M. E. Mackie, A. W. Kandel, Rapid increase in production of symbolic artifacts after 45,000 years ago is not a consequence of taphonomic bias. *J. Archaeol. Sci.* **160**, 105885 (2023).
78. B. Hayden, Archaeological Pitfalls of Storage. *Curr. Anthropol.* **61**, 763–793 (2020).
79. E. C. Ellis, N. Gauthier, K. Klein Goldewijk, R. Bliege Bird, N. Boivin, S. Díaz, D. Q. Fuller, J. L. Gill, J. O. Kaplan, N. Kingston, H. Locke, C. N. H. McMichael, D. Ranco, T. C. Rick, M. R. Shaw, L. Stephens, J.-C. Svenning, J. E. M. Watson, People have shaped most of terrestrial nature for at least 12,000 years. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2023483118 (2021).
80. R. Tipping, R. Bradley, J. Sanders, R. McCulloch, R. Wilson, Moments of crisis: Climate change in Scottish prehistory. *Proc. Soc. Antiq. Scot.* **142**, 9–25 (2013).
81. K. R. Kirby, R. D. Gray, S. J. Greenhill, F. M. Jordan, S. Gomes-Ng, H.-J. Bibiko, D. E. Blasi, C. A. Botero, C. Bowern, C. R. Ember, D. Leehr, B. S. Low, J. McCarter, W. Divale, M. C. Gavin, D-PLACE: A global database of cultural, linguistic and environmental diversity. *PLOS ONE* **11**, e0158391 (2016).
82. K. R. Kirby, R. D. Gray, S. J. Greenhill, F. M. Jordan, S. Gomes-Ng, H.-J. Bibiko, D. E. Blasi, C. A. Botero, C. Bowern, C. R. Ember, D. Leehr, B. S. Low, J. McCarter, W. Divale, M. C. Gavin, D-PLACE aggregated dataset, version v3.0.0 (Zenodo, 2024); https://doi.org/10.5281/ZENODO.10453887.
83. G. P. Murdock, D. R. White, Standard cross-cultural sample. *Ethnology* **9**, 329–369 (1969).
84. R. Dirks, Starvation and famine: Cross-cultural codes and some hypothesis tests. *Cross-Cult. Res.* **27**, 28–69 (1993).
85. P. J. Constantino, B. W. Wright, The importance of fallback foods in primate ecology and evolution. *Am. J. Phys. Anthropol.* **140**, 599–602 (2009).
86. P. N. Peregrine, Social resilience to climate-related disasters in ancient societies: A test of two hypotheses. *Weather Clim. Soc.* **10**, 145–161 (2018).
87. P. N. Peregrine, Social resilience to nuclear winter: Lessons from the Late Antique Little Ice Age. *Glob. Secur. Health Sci. Policy* **6**, 57–67 (2021).
88. M. Reichstein, F. Riede, D. Frank, More floods, fires and cyclones—Plan for domino effects on sustainability goals. *Nature* **592**, 347–349 (2021).
89. UN, UN Common Guidance on Helping Build Resilient Societies (2020); https://unsdg.un.org/resources/un-common-guidance-helping-build-resilient-societies.
90. R. Black, S. R. G. Bennett, S. M. Thomas, J. R. Beddington, Migration as adaptation. *Nature* **478**, 447–449 (2011).
91. S. A. Crabtree, J. A. Dunne, Toward a science of archaeoecology. *Trends Ecol. Evol.* **37**, 976–984 (2022).
92. J. A. d'Alpoim Guedes, S. A. Crabtree, R. K. Bocinsky, T. A. Kohler, Twenty-first century approaches to ancient problems: Climate and society. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 14483–14491 (2016).
93. R. O. Kaaronen, M. A. Manninen, E. Roe, J. I. Hukkinen, J. T. Eronen, Lessons for human survival in a world without ecological templates: What can we learn from small-scale societies? *Ecol. Soc.* **26**, art2 (2021).
94. C. Xu, T. A. Kohler, T. M. Lenton, J.-C. Svenning, M. Scheffer, Future of the human climate niche. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 11350–11355 (2020).
95. M. Scheffer, W. N. Adger, S. R. Carpenter, C. Folke, T. Lenton, G. Vince, F. Westley, C. Xu, Anticipating the global redistribution of people and property. *One Earth* **7**, 1151–1154 (2024).
96. L. Kemp, C. Xu, J. Depledge, K. L. Ebi, G. Gibbins, T. A. Kohler, J. Rockström, M. Scheffer, H. J. Schellnhuber, W. Steffen, T. M. Lenton, Climate endgame: Exploring catastrophic climate change scenarios. *Proc. Natl. Acad. Sci. U.S.A.* **119**, e2108146119 (2022).
97. C. Lyon, E. E. Saupe, C. J. Smith, D. J. Hill, A. P. Beckerman, L. C. Stringer, R. Marchant, J. McKay, A. Burke, P. O'Higgins, A. M. Dunhill, B. J. Allen, J. Riel-Salvatore, T. Aze, Climate change research and action must look beyond 2100. *Glob. Chang. Biol.* **28**, 349–361 (2022).
98. A. Ordonez, F. Riede, S. Normand, J.-C. Svenning, Towards a novel biosphere in 2300: Rapid and extensive global and biome-wide climatic novelty in the Anthropocene. *Philos. Trans. R. Soc. B* **379**, 20230022 (2024).

99. W. Thiery, S. Lange, J. Rogelj, C.-F. Schleussner, L. Gudmundsson, S. I. Seneviratne, M. Andrijevic, K. Frieler, K. Emanuel, T. Geiger, D. N. Bresch, F. Zhao, S. N. Willner, M. Büchner, J. Volkholz, N. Bauer, J. Chang, P. Ciais, M. Dury, L. François, M. Grillakis, S. N. Gosling, N. Hanasaki, T. Hickler, V. Huber, A. Ito, J. Jägermeyr, N. Khabarov, A. Koutroulis, W. Liu, W. Lutz, M. Mengel, C. Müller, S. Ostberg, C. P. O. Reyer, T. Stacke, Y. Wada, Intergenerational inequities in exposure to climate extremes. *Science* **374**, 158–160 (2021).
100. J. Gowdy, Our hunter-gatherer future: Climate change, agriculture and uncivilization. *Futures* **115**, 102488 (2020).
101. J. C. Jiménez, I. Romanowska, R. Raja, E. H. Seland, Food security in Roman Palmyra (Syria) in light of paleoclimatological evidence and its historical implications. *PLOS ONE* **17**, e0273241 (2022).
102. F. Riede, Climate models: Use archaeology record. *Nature* **513**, 315 (2014).
103. L. E. Lisiecki, M. E. Raymo, Plio–Pleistocene climate evolution: Trends and transitions in glacial cycle dynamics. *Quat. Sci. Rev.* **26**, 56–69 (2007).
104. U. Niemeier, F. Riede, C. Timmreck, Simulation of ash clouds after a Laacher See-type eruption. *Clim. Past* **17**, 633–652 (2021).
105. F. Zhu, J. Emile-Geay, G. J. Hakim, J. King, K. J. Anchukaitis, Resolving the Differences in the Simulated and Reconstructed Temperature Response to Volcanism. *Geophys. Res. Lett.* **47**, e2019GL086908 (2020).
106. D. O'Sullivan, G. L. W. Perry, *Spatial Simulation: Exploring Pattern and Process* (John Wiley & Sons, 2013); http://patternandprocess.org/.
107. I. Romanowska, C. D. Wren, S. A. Crabtree, *Agent-Based Modeling for Archaeology: Simulating the Complexity of Societies* (SFI Press, 2021).
108. V. Grimm, S. F. Railsback, C. E. Vincenot, U. Berger, C. Gallagher, D. L. DeAngelis, B. Edmonds, J. Ge, J. Giske, J. Groeneveld, A. S. A. Johnston, A. Milles, J. Nabe-Nielsen, J. G. Polhill, V. Radchuk, M.-S. Rohwäder, R. A. Stillman, J. C. Thiele, D. Ayllón, The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism. *J. Artif. Soc. Soc. Simul.* **23**, 7 (2020).
109. V. Grimm, U. Berger, F. Bastiansen, S. Eliassen, V. Ginot, J. Giske, J. Goss-Custard, T. Grand, S. K. Heinz, G. Huse, A. Huth, J. U. Jepsen, C. Jørgensen, W. M. Mooij, B. Müller, G. Pe'er, C. Piou, S. F. Railsback, A. M. Robbins, M. M. Robbins, E. Rossmanith, N. Rüger, E. Strand, S. Souissi, R. A. Stillman, R. Vabø, U. Visser, D. L. DeAngelis, A standard protocol for describing individual-based and agent-based models. *Ecol. Model.* **198**, 115–126 (2006).
110. G. P. Murdock, D. R. White, D-PLACE dataset derived from Murdock and White 1969 "Standard Cross-Cultural Sample," version v3.1 (Zenodo, 2024); https://doi.org/10.5281/ZENODO.13318864.
111. G. P. Murdock, R. Textor, I. H. Barry, D. R. White, J. P. Gray, W. T. Divale, D-PLACE dataset derived from Murdock et al. 1999 "Ethnographic Atlas," version v3.1 (Zenodo, 2024); https://doi.org/10.5281/ZENODO.13319191.
112. G. P. Murdock, R. Textor, H. Barry, D. R. White, J. P. Grey, W. Divale, Ethnographic Atlas. *World Cultures* **10**, 24–136 (1999).
113. L. R. Binford, *Constructing Frames of Reference: An Analytical Method for Archaeological Theory Building Using Hunter-Gatherer and Environmental Data Sets* (Univ. of California Press, 2001).
114. L. R. Binford, D-PLACE dataset derived from Binford 2001 "Constructing Frames of Reference," version v3.1 (Zenodo, 2024); https://doi.org/10.5281/ZENODO.13319363.
115. J. G. Jorgensen, D-PLACE dataset derived from Jorgensen 1980 "Western Indians," version v3.1 (Zenodo, 2024); https://doi.org/10.5281/ZENODO.13318637.
116. J. G. Jorgensen, Western Indians: Comparative Environments, Languages, and Cultures of 172 Western American Indian Tribes (W. H. Freeman, 1980).

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