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A forward-looking approach to climate change and the risk of societal collapse

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A B S T R A C T

This article proposes a forward-looking approach to studying societal collapse risks related to climate change. Such an approach should indicate how to study emerging collapse risks and suggest strategies for adapting to them. Our approach is based on three postulates that facilitate a forward-looking approach: (1) collapse, if it occurred, would be a lengthy process rather than an abrupt event; (2) significant collapse risks already exist in some places; and (3) diminishing returns on adaptation to intensifying climate impacts are a key driver of collapse risks. The first two postulates suggests that collapse risks can be studied in process, while the third points to strategies for adaptation pathways that avoid unsustainable diminishing returns. Applying diminishing returns to climate change adaptation, rather than sociopolitical complexity or resource extraction, is also a novel theoretical contribution to collapse literature.

1. Introduction

A number of authors have discussed mechanisms by which anthropogenic climate change could risk societal collapse on a global scale (Abegão, 2022; Avin et al., 2018; Beard et al., 2021; Gowdy, 2020; Kemp et al., 2022; Richards, Lupton, & Allwood, 2021; Steel, DesRoches, & Mintz-Woo, 2022). However, the collapse of contemporary societies due to anthropogenic climate change (in brief, *climate collapse*) is inherently difficult to study. While there are instances of societal collapse in the historical and archeological records (Butzer, 2012; Middleton, 2017; Tainter, 1988), the massively larger, wealthier and more technologically complex scale of contemporary societies along with unprecedented climatic conditions likely to confront humanity in the not-too-distant future create significant uncertainties for generalizations about future collapse risks from past cases. In this article, then, we propose a novel theoretical approach to studying societal collapse risks related to climate change.

We suggest that a useful theoretical approach for studying climate collapse risks should be forward-looking. To start with, that means it cannot be limited to after-the-fact explanations. Whereas archeologists and historians strive to understand the causes of past

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collapses, climate change focuses attention on present and future risks. In addition, a forward-looking approach should provide practical guidance on sustainable adaptation pathways in the face of climate change.

Our theoretical approach is based on the following three postulates that follow from this forward-looking perspective:

1. If global climate collapse were to occur, it would unfold over an extended period of time.
2. Localized risks of climate collapse are already apparent in some places.
3. Diminishing returns to adaptation given intensifying climate impacts are a key driver of collapse risks.

These postulates embody the key features noted above. If collapse is an extended process rather than an abrupt event and localized risks of collapse already exist, then mechanisms underlying those risks can be studied in the present. And the third postulate prompts creative thinking about alternate, more sustainable adaptation pathways that reduce risks of diminishing returns.

In addition, postulate (3) advances theorizing about collapse by applying diminishing returns to adaptation given intensifying climate change. While diminishing returns is an important concept in prior work on collapse, it has been applied to sociopolitical complexity (Tainter, 1988) or resource extraction (Bardi et al., 2019). Diminishing returns to adaptation given intensifying climate impacts is a simpler alternative. It does not require assumptions linking climate change to sociopolitical complexity and can be readily applied to societies, like small island states, with negligible resource extraction and greenhouse emissions. Finally, our approach explains how climate change, by threatening international cooperation, may encourage adaptive strategies with greater risks of diminishing returns.

The organization of this article is as follows. Section 2 identifies three explanatory themes in prior literature on societal collapse that are relevant to climate change: diminishing returns, environmental impacts, and complex systems. Section 3 expands on our theoretical approach and explains its advantages for studying risks of societal collapse linked to climate change. Section 4 discusses two case studies in connection with our proposal: the small island state of Tuvalu and food security. Section 5 concludes.

2. Three explanatory themes

In this section, we discuss three themes found in explanations of societal collapse: *diminishing returns*, *environmental impacts*, and *complex systems*. These themes are not intended to be exhaustive of the literature, but rather are strands that we regard as most relevant to understanding how climate change may lead to collapse.[3] A common feature of these explanations is that they have relatively little to say about what forms of adaptation most effectively reduce climate collapse risks.

2.1. Diminishing returns

The first explanatory theme emphasizes a dynamic of diminishing returns hypothesized to flow from the basic structure of the society. The most influential representative of this approach is Tainter (1988), who explains collapse in terms of diminishing returns on sociopolitical complexity. Tainter claims that solutions to societal problems require ever-increasing levels sociopolitical complexity, understood as centralized hierarchical organization and a broad diversity of social identities and professions (1988, p. 23). Tainter (1988) argues that there is a strong tendency for diminishing returns on social complexity. Growing societies, according to Tainter, require ever increasing social complexity to address challenges, but the marginal return on investments in complexity tends to decrease, creating vulnerability to collapse. For example, Tainter suggests that early conquests by the Roman Empire were extremely profitable, funding further conquests, an expanded military, infrastructure projects, and an administrative apparatus. However, as centuries wore on, conquests became more costly and yielded smaller returns, leaving Rome in a predicament of maintaining armies, infrastructure, and administrative systems that were too expensive for its agriculturally-based economy to support. Building on Tainter's work, Janssen et al. (2003) suggest that the human tendency to cling to sunk costs, such as irrigation works, explains why some societies become stuck on an unsustainable pathway of diminishing returns.

Tainter suggests two ways that declining returns on sociopolitical complexity can lead to collapse (1988, pp. 195–196). The first is that diminishing returns lead to a steady erosion of resources and reserve capacity, which in turn reduces societal resilience and the ability to cope with shocks, such as natural disasters or invasions. The second is that diminishing returns on complexity makes reversion to a simpler sociopolitical form an appealing option, which may result in the disintegration of centralized political and economic control.

A central theme in Tainter's (1988) work is that crises, sparked for instance by droughts, invasions or incompetent leadership, are inadequate explanations of collapse (pp. 206–207). According to Tainter, societies necessarily learn to adapt to perturbations of various kinds, and sometimes survive an earlier crisis only to collapse in the face of a similar one later (see also Butzer, 2012; Butzer & Endfield, 2012). Thus, Tainter argues, a theory of collapse must explain how a society's resilience is undermined, thereby leaving it vulnerable to crises. For Tainter, diminishing returns on sociopolitical complexity is the key explanatory factor.

Bardi et al. (2019) follow Tainter (1988) in emphasizing diminishing returns, but they differ in associating these with resource

[3] Rubiños and Anderies (2020) provide a longer list of explanatory approaches than our three themes. In part this is a splitting-versus-lumping difference. For instance, selfish elites, noted as collapse explanations by Rubiños and Anderies (2020), seem relevant to climate change as factors that may exacerbate environmental impacts. However, some proposed explanatory factors of collapse, such as centralized government, are rarely mentioned in connection with climate change and so are not discussed here.

extraction rather than sociopolitical complexity. Thus, while Tainter (1988) attributes the fall of the Roman Empire to difficulties of maintaining a complex state apparatus and military, Bardi et al. (2019) blame the declining productivity of silver mines in Spain that made the empire unable to pay its legions (see also Bardi, 2017). Bardi et al. (2019) present a model in which non-renewable resources feed various sectors of a complex society, which in turn regulate the extraction and use of those resources. Diminishing returns occur as a result of extracting the most easily accessed resources before moving on to more difficult-to-get reserves. Over time, the ratio of resource to extraction cost declines, so ever larger investments must be made to extract resources and continue the growth of the society. However, since the resources are not renewable, the process is unsustainable and eventually ends in collapse if no new resource is found. Bardi et al. (2019) suggest that collapse is often short in comparison to the time the society took to rise to its zenith, a pattern they call “Seneca collapse” (see also Bardi, 2017).

Despite their differences, both Tainter and Bardi et al. (2019) suggest contemporary societies will ultimately have to find new energy sources if they are to avoid collapse (Tainter, 1988, p. 215). In the context of climate change, such claims might be interpreted as calling for a transition from fossil fuels to renewables. Tainter (1995, 2006) also argues that, since new resources and innovations are needed to stave off collapse risks, sustainability requires continual societal growth. However, beyond these broad suggestions, it is unclear what diminishing returns suggests about which adaptation strategies best reduce climate collapse risks.

2.2. *Environmental Impacts*

The second explanatory theme emphasizes environmental perturbations, whether exogenous or self-inflicted, that surpass limits of adaptation. Weiss and Bradley (2001), who emphasize climatic shifts as causes of past civilization collapses, provide a good example. They characterize the climatic changes they discuss as “unprecedented” (p. 610), apparently to explain why societies could not have been expected to adapt to them.

An important variation on the environmental impact theme emphasizes overshoot of ecological boundaries, for instance, due to intensive agriculture (Diamond, 2005). Proponents of ecological overshoot explanations often see past collapses as analogues of current environmental problems, with overpopulation and overconsumption being salient concerns (Abegão, 2022; Ehrlich & Ehrlich, 2013; Fanning et al., 2022). For example, Abegão (2022) argues that the human population has continued to exceed its safe operating space, so that individuals exceed their per capita limit of natural capital (productive land) while saturating natural emission sinks. Ecological overshoot explanations tend to emphasize human short-sightedness and resulting environmental catastrophes, rather than diminishing returns of locked-in social, political or economic structures.

Related explanations of collapse are suggested by literature on threats to key planetary boundaries, such as collapse of ice sheets and biodiversity loss (Armstrong McKay et al., 2022; Lenton et al., 2008, 2023; Rockström et al., 2009; Steffen et al., 2015, 2018). Here, the idea is that small changes in Earth subsystems (e.g., the summer monsoon system in India) at critical thresholds (e.g., tipping points, planetary boundaries) can trigger self-reinforcing and irreversible changes to the global climate system. Rockström et al. (2009) describe human reliance on fossil fuels and industrial agriculture as the main means by which planetary boundaries (e.g., thresholds for ocean acidification and rates of biodiversity loss) are exceeded. Other authors suggest that climate change may lead to temperature and precipitation regimes that push much of the Earth’s surface outside of climatic niches in which large human populations have been concentrated throughout history (Lenton et al., 2023; Xu, Kohler, Lenton, Svenning, & Scheffer, 2020).

In work on planetary boundaries, risk of societal collapse is typically an implied consequence rather than explicitly discussed (Armstrong McKay et al., 2022; Fanning et al., 2022; Lenton et al., 2008, 2023; Rockström et al., 2009; Xu et al., 2020). Outcomes plausibly related to collapse are often mentioned, such as significant negative impacts on human welfare (Armstrong McKay et al., 2022; Fanning et al., 2022; Lenton et al., 2008), moving much of the world’s population outside of its historical climate niche (Lenton et al., 2023; Xu, Kohler, Lenton, Svenning, & Scheffer, 2020), or irreversible environmental changes that may have “deleterious and potentially disastrous consequences for humans” (Rockström et al., 2009, p. 472). However, the word “collapse” and equivalent terms are almost never used in connection with human societies in this literature.

However, some have explicitly considered connections between collapse and scientific literature on planetary boundaries and climatic tipping points. For example, Gowdy (2020) claims that large-scale agriculture and urban centers typical of contemporary civilization depend on the stable climatic conditions of the Holocene, and thus that crossing climate tipping points and planetary boundaries will create a post-Holocene world where agriculture on a scale sufficient to feed billions of people is impossible. Whether by collapse or orderly transition, Gowdy predicts the end to contemporary industrial civilization and a return to hunter-and-gathering within the next 200 years (p. 7). In contrast, Lenton (2023) rejects the idea of a stable Holocene and considers how a shrinking human climate niche might create collapse risks. Lenton proposes that collapse occurs when a complex system crosses a tipping point that leads from a higher to a lower state of complexity. This might happen as the result of a random event like an earthquake (noise-induced tipping), abrupt climate change (rate-dependent tipping), gradual climatic changes that overwhelm adaptive capacities (bifurcation-tipping), or maladaptive responses to climate impacts (endogenous evolution to a bifurcation tipping point) (Lenton, 2023). The last of these scenarios suggests that reduction of the human climate niche might result in collapse due to conflict induced by large-scale migration.

While they call attention to the dangers of climate change, explanations considered in this subsection do not, to our knowledge, link collapse risks to climate change adaptation.

2.3. *Complex Systems*

The third explanatory theme foregrounds the propagation of risks through complex social systems, such as trade and international politics, that involve feedback loops and spillover effects where an initial shock (e.g., an extended drought) instigates maladaptive behaviors (e.g., conflict) that intensifies collapse risks and causes them to spread. For example, Cline (2021) portrays the end of the Late Bronze Age as a "perfect storm" (p. 165) of invasions, natural disasters, and climatic shifts that rippled through a network of kingdoms linked by trade and political alliances.

Literature on existential and global catastrophic risks often links collapse to vulnerabilities of complex systems (Avin et al., 2018; Beard et al., 2021; Kareiva & Carranza, 2018; Kemp et al., 2022). For example, Avin et al. (2018) consider collapse in connection with critical systems that perform life-sustaining functions for humans, breakdowns in these critical systems that can instigate mechanisms that spread catastrophic risks, and factors spanning individual and institutional scales that may hinder prevention and mitigation efforts. However, apart from two brief mentions of geo-engineering, Avin et al. (2018) do not connect their framework to climate change. Other work in this genre focuses on climate change more specifically. For example, Beard et al. (2021) discuss a "Global Death Spiral" in which adverse ecosystem impacts of climate change lead to food shortages, and then to political consequences such as state failure and increased conflict, which in turn obstruct efforts to mitigate and adapt to climate change. A related analysis is found in Richards et al. (2021), who examine disruptions to food production and trade as a potential collapse mechanism. They explore the dynamics of global food markets (e.g., how food subsidies affect food price, and in turn food accessibility), addressing factors that could drive collapse at the nation level, and how their effects could ramify to the global scale by threatening food insecurity, which in turn triggers social unrest and emigration.

Some of the work discussed in this subsection makes suggestions about adaptations that can reduce collapse risks. For example, Beard et al. (2021) recommend reducing institutional barriers to risk reduction, preparing institutional responses for severe crises, and encouraging modularity and redundancy within systems (p. 10). These recommendations are relevant to our discussion of food security in Section 4.2.

3. A forward-looking approach to climate collapse risks

A forward-looking approach aims to study collapse risks in the present and suggest adaptations in response to them. We begin by explaining how we understand the term "collapse." Then we expand on the three theoretical postulates mentioned in the introduction: (1) collapse, if it occurs, would be an extended process rather than an abrupt event; (2) localized climate collapse risks are already apparent in some places; and (3) diminishing returns on adaptation to intensifying climate impacts are a key driver of collapse risks. We explain the rationale of each postulate and explain how they foster a forward-looking approach.

We understand *collapse* to be a reduction of collective capacity,[4] defined as material and organizational capacities to create mutual benefits or support societal goods, resulting in a difficult to reverse loss of basic functionality. Loss of basic functioning in a society entails a widespread inability to meet essential needs of its population, such as physical security, housing, and food. According to this definition, loss of features like political centralization and control (Renfrew, 1979), an established level of sociopolitical complexity (Tainter, 1988), or system identity (Cumming & Peterson, 2017) are indicative of collapse only insofar as they are tied to a reduction of societal capacity that leads to a difficult to reverse loss of basic functioning. For example, if a transition from dictatorship to democracy results in improved economic conditions and reduced government corruption, then collapse has not occurred, despite the decline of political centralization and control. Similarly, an empire that fragments into independent functional states has undergone a loss of established sociopolitical complexity, but has not experienced societal collapse. And socioeconomic transformations such as the industrial revolution or the renewable energy transition, if it occurs, can change system identity without causing collapse.

Our concept of collapse has several advantages when it comes to climate change. The focus on collective capacity to carry out core functions, such as meeting basic needs of a population, directly explains why climate collapse risks should be an urgent concern. By contrast, traditional definitional criteria of collapse, like loss of sociopolitical complexity (Tainter, 1988) and political decentralization/fragmentation (Renfrew, 1979; Kemp et al., 2022), appear morally significant only insofar as they adversely impact collective capacities needed for valuable societal functions. Our concept can also be applied to any social entity that possesses collective capacity. That includes states, supra-state entities like the European Union, trade networks and organizations of various types.

Like our definition of collapse, our three postulates are intended as plausible starting points for a theoretical approach to studying collapse risks associated with climate change. Consider, then, our first postulate that societal collapse due to climate change would be a lengthy process. Discussions of societal collapse often differ about how quickly it must happen. Some definitions of collapse require it to be rapid (e.g., Tainter, 1988), and some even specify a short interval, such as less than 25 years (Cumming & Peterson, 2017). However, other authors emphasize that collapse is rarely fast and observe that time spans associated with well-known archeological or historical collapses, like the fall of the Western Roman Empire and the Classic Maya, often span a century or more (Butzer, 2012). Bardi's (2017) Seneca collapse, according to which collapse is shorter than the rise, does not require collapse to occur in a single human generation. For example, the fall of the Western Roman Empire is usually thought to have taken more than two centuries, but the time it took the Empire to emerge may have been much longer, depending on where one puts the starting date (Bardi, 2017). Our postulate (1) is compatible with Seneca collapse and only rejects the idea that climate collapse must be quick in absolute terms.

There are several reasons why societal collapses, especially at large scales, would unfold over an extended period of time. All societies possess adaptive capacity, and societies with a high degree of capacity are likely to exert substantial efforts to protect valuable natural, material, and human capital. An encroaching threat may be fended off for decades or even centuries; cities and other

[4] Collective capacity differs from the related concept of state capacity (Berwick & Christia, 2018) in not being restricted to states.

infrastructure may be rebuilt after a disaster; production may be intensified; and reforms may be enacted. These considerations are especially pertinent when one considers contemporary threats posed by climate change to global society, whose resources and adaptive capacities far outstrip its historical predecessors.

Postulate (1) supports a forward-looking approach. If climate collapse is a lengthy process rather than an abrupt event, then it may be possible to study collapse risks as they unfold. Furthermore, such risks are unlikely to progress uniformly across the globe, as vulnerability to climate-related disruptions is distributed unequally and the emergent signal of climate impacts is stronger and earlier in some places than others (Mahlstein et al., 2011; Thomas et al., 2018). That leads to our second postulate, according to which significant risks of climate collapse are already present in some places.

The strongest rationale for postulate (2) is simply to give examples. Many coral atolls are at risk of becoming uninhabitable within this century due to salinization of aquifers, land erosion, impacts on food supply, and other factors (Duvat et al., 2021; Storlazzi et al., 2018). Similarly, extreme heat, water scarcity, and desertification are threats to communities in the Middle East (Adamo et al., 2022) and African drylands (Thalheimer et al., 2021). In general, societal vulnerability to climate impacts depends on exposure, sensitivity, and adaptive capacity, which are in turn tied to local climatic, social, political, and economic conditions (Thomas et al., 2018). A natural approach to the empirical study of climate collapse, therefore, is to begin in places where risks are the most severe and imminent. Note that postulate (2) speaks of collapse *risks*, not collapse itself. This shift in emphasis is necessary in a forward-looking approach, which aims to study mechanisms that might lead to collapse in order to reduce the probability that collapse will occur.

While postulates (1) and (2) entail that it is possible to study collapse risks in the present, our third postulate says something about what to look for. Postulate (3) states that diminishing returns on adaptation to intensifying climate impacts are a driver of collapse risks. Diminishing returns involve a declining ratio of benefits to costs as more resources are expended. In the case of adaptation, the benefit is reduced risk while costs include financing and negative externalities. If the adaptation is a higher seawall, then the benefit is lower risk of flooding while costs include money needed for construction and maintenance along with negative side-effects like reduced access to the sea or destruction of coastal habitats.[5] Postulate (3) is concerned with how the marginal benefit-to-cost ratio of adaptation can decline over time as climate change intensifies.

Consider this idea in connection with the example of a seawall to protect a coastal community from rising sea levels and storm surges. Construction costs and negative externalities are likely to increase as the sea wall rises (Diaz, 2016), and to do so in a faster-than-linear manner. For instance, a two-meter seawall requires a broader base and hence more than twice the materials of a one-meter seawall. Moving more than twice the materials and raising them to greater heights requires more than twice the energy, larger cranes, and so on. Consequently, the construction costs of adapting to the second meter of sea level rise would likely be greater than for the first. The tendency of construction costs to increase with scale is one way that adaptation to intensifying climate change can face diminishing returns. Negative externalities can also exhibit cost-scaling effects. For example, a two-meter wall obstructs ocean views much more than a one-meter wall. Scaling-effects of negative externalities can follow the "low hanging fruit" pattern common to diminishing returns, in which lower-cost solutions or resources are exploited first (Bardi et al., 2019). For example, when dredging sand for a coastal reclamation project one might first draw from areas without fragile marine ecosystems. But with growing scale, it may become necessary to dredge from more sensitive locations, such as coral reefs. Rising negative externalities with scale can also involve broader systemic impacts, as illustrated by the example of food stockpiling and food prices in Section 4.2.

Diminishing returns on adaptation can also arise from transforming the risk towards more severe harms. For example, a higher seawall may reduce the probability of flooding while increasing the severity of flooding that does occur by encouraging people to settle in areas protected by the wall and by obstructing drainage if the wall is breached (Schipper, 2020, p. 412). Since risk equals the probability of harm multiplied by its severity, this entails a downward pressure on the risk reduction accruing from an additional meter of seawall. Thus, even if each meter of seawall reduces the probability of flooding to the same extent as the previous one, the benefits may decrease.

When combined with a steadily intensifying risk, diminishing returns on adaptation are a recipe for unsustainability. Further adaptation is persistently needed but becomes more expensive with every step. If the costs rise more quickly than the wealth of the society, adaptation and protection from intolerable harms may eventually become unaffordable or impossible. That would entail crossing a limit to adaptation (Dow et al., 2013), which might lead to collapse. This sort of scenario is already a serious concern for small island developing states like Tuvalu, as discussed below in Section 4.1. However, diminishing returns on adaptation may create risks of collapse before a limit to adaptation is reached. Rising adaptation costs might draw down a society's resources making it vulnerable to collapse triggered by other crises. Or rising costs and decreasing benefits of an adaptation strategy may make alternatives that undermine societal capacities, such as unmanaged retreat, attractive alternatives. As Tainter (1988) argued, diminishing returns in the face of a rising risk are important for understanding how the resilience of even well-resourced societies can be worn down.

Furthermore, rising climate impacts can threaten forms of cooperation that are essential for adaptation and prompt actions that lead down a path of diminishing returns. Cooperation can be an adaptive strategy against climate risks like extreme weather events or crop failure. For example, free international food trade can act as a buffer against shortfalls of domestic crop production. However, the efficacy of free trade as an adaptation to protect food insecurity depends on prices remaining in an affordable range. As a result, price shocks, which may become more common due to disruptions to agriculture associated with climate change, can result in extreme public pressure on governments to enact measures such as export restrictions, subsidies for domestic production and stockpiling, as discussed in Section 4.2. Yet export restrictions and stockpiling by one country can result in higher prices in international markets,

[5] Benefits and costs may be easily monetizable (e.g., financial costs of building a seawall) or not (e.g., reduced marine biodiversity).

increase food insecurity for consumers internationally, and thus ramp up pressure on more governments to impose export restrictions and stockpiling. Finally, food subsidies and stockpiling by individual governments are likely to confront diminishing returns in the face of intensifying climate change in a similar manner to building ever-higher seawalls.

Diminishing returns on adaptation are not inevitable. Adaptations can be more or less prone to rising costs with scale and increased severity of harms (Schipper, 2020). We discuss several examples to illustrate this point in Section 4. Steering societies in the direction of non-collapse forms of transformation (cf. Mach & Siders, 2021), therefore, should be a central objective of climate adaptation policies. We suggest that avoiding unsustainable diminishing returns on adaptation is a key element in achieving this objective.

Applying diminishing returns to adaptation, rather than to sociopolitical complexity (Tainter, 1988) or resource extraction (Bardi et al., 2019), makes our proposal better able to provide guidance about adaptation. In our approach, diminishing returns may be generated by features of the adaptations themselves, rather than by the complexity of the society that implements them. That means societies may be able to choose adaptation strategies that avoid diminishing returns. The level of complexity of one's society is, by contrast, more of a background condition than a policy option. Furthermore, our approach avoids problematic assumptions. Our proposal is compatible with attributing climate collapse risks to burning fossil fuels rather than sociopolitical complexity per se. And while we agree with Tainter that adaptation requires resources and innovations, we do not assume that solutions always involve increased sociopolitical complexity. Coastal mangrove forests, for example, may be both simpler and more sustainable forms of adaptation to rising seas than the construction of vast seawalls (Turner et al., 2022). Nor need we link climate collapse to diminishing returns on resource extraction. After all, limitless supplies of cheap fossil fuels would weaken economic incentives for transitioning to renewables. And diminishing returns on climate adaptation can arise for countries with minimal resource extraction and greenhouse gas emissions. The advantages of our approach are illustrated by the examples discussed below.

4. Examples

In this section, we discuss two examples, the small island state of Tuvalu and food security, to illustrate our approach to studying collapse risks. Both illustrate the link between diminishing returns on adaptation and collapse risks, and consequently the need to seek adaption pathways that avoid unsustainable diminishing returns.

4.1. Tuvalu

Tuvalu is a remote atoll nation in the South Pacific, made up of nine small, scattered islands, with a population of approximately 11,000 (New Zealand Ministry of Foreign Affairs and Trade, 2021). Like other small island developing states, it is particularly vulnerable to sea level rise (SLR), as it currently sits at only 1.83 m above sea level, on average, with a rate of SLR that is already high compared to the global average (~5 mm per year since 1993 as compared to 2.8–3.6 mm per year) (New Zealand Ministry of Foreign Affairs and Trade, 2021; Tuvalu Meteorological Service, & Pacific Climate Change Science Program, 2011). Vulnerabilities associated with Tuvalu's natural environment are its small size, isolation, low soil fertility, and general poor conditions for agriculture (Tui & Fakhruddin, 2022). Nevertheless, this landscape is of great importance to the people of Tuvalu, and strong place-based attachments exist that are based in lifestyle, culture, ancestral connections, spirituality, and identity (Farbotko & Campbell, 2022; Mortreux & Barnett, 2009).

Tuvalu also has immense economic vulnerability to the effects of climate change. Its main sources of revenue are international aid, fishing (mostly proceeds from fish licenses distributed to foreign fleets in exchange for access to Tuvalu's exclusive economic zones), distributions from the Tuvalu Trust Fund, and tax revenue, the latter of which is the only revenue stream generated within Tuvalu (Iulai, 2014, pp. 5). The nation relies on imported foods, but trading and shipping services are often hindered by extreme weather (International Organization for Migration Fiji, & International Labour Organization, 2021; Tui & Fakhruddin, 2022). Up to 60% of revenue comes from the fisheries sector alone, and subsistence fishing and agriculture are a source of livelihood for the majority of its population, making Tuvalu highly dependent on the health of its marine resources, which are jeopardized due to climate change (Australian Government Department of Foreign Affairs and Trade, 2023; New Zealand Ministry of Foreign Affairs and Trade, 2021).

Sea-level rise is projected to worsen throughout the century in Tuvalu, by 4–14 cm under a low emissions scenario (Tuvalu Meteorological Service, & Pacific Climate Change Science Program, 2011). Interactions between SLR and other climate-related variables such as storms and wave dynamics contribute to infrastructure damage, freshwater salinization, coastal erosion, and land habitat loss, and these impacts are worsening over time (McMichael et al., 2020). Annual wave-driven overwash events will repetitively damage both land and infrastructure, while also contaminating the island's freshwater sources with salt water (Storlazzi et al., 2018). Freshwater stress will be enhanced by projected increases in droughts and reduced annual precipitation under rising global temperatures (Thomas et al., 2020), and aquifers will gradually not be able to replenish between overwash events (Storlazzi et al., 2018). Storms will intensify, with a projected increase in the intensity of tropical cyclones that bring with them more waves and flood risks (Tuvalu Meteorological Service, & Pacific Climate Change Science Program, 2011). Besides flooding phenomena, rising temperatures will increase marine and terrestrial heatwaves (Thomas et al., 2020).

There are three main types of adaptation strategies in coastal regions: protect, accommodate, and retreat (Diaz, 2016). Protection strategies fall into "hard" measures, which encompass physical, built infrastructure such as seawalls and dikes to stave off flooding and "soft" measures, which involve the restoration of natural barriers in coastal ecosystems (e.g., beach nourishment and mangrove rehabilitation programs) (Diaz, 2016; Martyr-Koller et al., 2021; Nicholls, 2011; Yarina & Takemoto, 2017). Accommodation strategies reduce the impacts of flooding, for example by raising or flood-proofing infrastructure and housing, while retreat involves moving people and capital (assets, etc.) away from the hazard (Diaz, 2016). Protection costs increase along with sea levels, as higher seawalls are associated with higher construction costs (Diaz, 2016). Such infrastructure also has annual maintenance costs, opportunity costs associated with the lost land, and can incur externalities like erosion (Diaz, 2016). For example, these efforts involve dredging, which will have more severe impacts on reefs and marine ecosystems the more extensive the dredging is (Kitara, 2019). Consequently, rising costs with scale, and hence diminishing returns, are likely to confront efforts to protect Tuvalu from rising seas by land reclamation and seawalls.

In contrast, retreat tends to be more cost-effective than protection on the whole, and planned retreat on the whole is more cost-effective than reactive retreat (Diaz, 2016). However, coral atolls like Tuvalu possess little in the way of higher ground to retreat to, thereby severely constraining their ability to employ internal retreat as an adaptation strategy in the face of rising seas (Martyr-Koller et al., 2021). For small island states like Tuvalu, then, retreat implies outward migration of the population to other states. Thus, while relocation may be less prone to unsustainable diminishing returns than protection and accommodation, it also risks devolving into a collapse where Tuvalu ceases to exist as a functioning society and state.

However, it may be possible for Tuvalu to relocate while avoiding collapse. Doing so would require the cooperation and support of other states, for example, that would permit settlement by Tuvalu émigrés and allow the Tuvalu government a reasonable degree of autonomy in providing services to its population, maintaining its culture, and representing its interests internationally (Burkett, 2011; Kitara, 2019). In this scenario, Tuvalu would become a microstate whose population resides in host nations. Such an eventuality would require revenue streams for the Tuvalu government, for instance, from license fees from commercial fishing fleets operating in Tuvalu's current territorial waters (Kitara, 2019). However, international law is unclear on whether Tuvalu could retain title to its Exclusive Economic Zone, which would be necessary in order to continue collecting fishing license fees, in the event that its government was relocated (Yamamoto & Esteban, 2010). Countries with greater historical emissions arguably have a moral obligation to assist Tuvalu's transition to an ex-situ state should this become necessary (Kitara, 2019; pp. 1, 1231; Wündisch, 2019).

Tuvalu illustrates the intersections of diminishing returns, collapse risks, and moral responsibilities related to climate change. Adaptation in place entails willingness of donor countries to accept rising costs associated with diminishing returns, which they arguably have a moral obligation to do. But Tuvalu can avoid collapse even if it becomes uninhabitable, provided that other states support the emergence of ex-situ statehood. Avoiding collapse, then, may involve societal transformations to support forms of adaptation that are less susceptible to diminishing returns.

4.2. Food security

In this subsection, we consider the potential for diminishing returns on adaptations intended to safeguard food security in the face of climate change. Food security has four main components: availability (i.e., food production and supply), access (i.e., the ability to purchase or otherwise acquire food), utilization (i.e., the nutritional uptake of food consumption), and stability (i.e., the propensity of the previous components to be consistently satisfied) (Food and Agriculture Organization of the United Nations, 2008). Our discussion focuses on access and stability, and specifically risks arising from international food price shocks. This example illustrates how breakdowns of international cooperation can encourage adaptation strategies that risk unsustainable diminishing returns.

Climate change poses risks to agriculture, and yield impacts in wheat, maize, rice, and soybean production are of particular concern, as these four staple breadbasket crops provide two-thirds of food calories consumed globally (Kim et al., 2019). Extreme weather events including heat waves, droughts, and floods are major drivers of yield failure and are becoming more frequent and intense due to climate change (Mehrabi, 2020). Phenomena such as the El Niño Southern Oscillation, which is a regularly repeating oscillation in large-scale sea-surface temperatures, are important modifiers of crop-yield variation, are linked with the occurrence of extreme weather events in several regions at once and are becoming more intense during climate change (Funk et al., 2018; Gaupp et al., 2020; Hasegawa et al., 2022; Iizumi et al., 2014). Co-occurring shocks can enhance joint breadbasket failures, such as across multiple growing regions for maize (Kornhuber et al., 2023; Tigchelaar et al., 2018), or across more than one of the four different staple breadbasket crops, in what are termed multi-breadbasket failure events (Mehrabi, 2020). The probabilities of both single and joint breadbasket failures are projected to increase in the next 30 and 50 years (Caparas et al., 2021; Kornhuber et al., 2023). Crop failure events lead to price shocks, so more frequent multi-breadbasket failures may result in more frequent and volatile spikes in the prices of staple crops (Hasegawa et al., 2022; Headey & Fan, 2010; Mehrabi, 2020).

Food security, then, is an important goal of climate change adaptation. International food trade unburdened by import tariffs, export restrictions, and production subsidies can be seen as an adaptation that protects food security in the face of climate change and other threats (Anderson, 2022; Baldos & Hertel, 2015). From this perspective, market forces favor food production where it has a competitive advantage, and if one country's agricultural output declines in a year, it can increase the quantity it imports from countries where yields are higher. Supporters of global free trade of food thus insist that it brings down prices and reduces poverty (Anderson, 2022). International free trade of food is a form of economic cooperation among governments with differing interests, including food importing and exporting nations. In general, cooperation involves opportunity costs of refraining from selfish actions in the expectation of a larger or longer-term benefit. In the case of free international trade of food, opportunity costs could mean not implementing import tariffs and subsidies to protect politically influential domestic producers from foreign competition, or not imposing export restrictions to capture domestic supply when prices rise.

Increased frequency of food supply shocks due to climate change and subsequent price volatility threaten the usefulness of international food trade as a safeguard of food security (Hopewell & Margulis, 2023; Margulis et al., 2023). As Sen (1983) argued, famine need not result from absolute scarcity: food prices too high for a population to pay can suffice. Dependence on international food trade, therefore, may leave a government without effective solutions to acute food insecurity brought on by a spike in prices (Hopewell & Margulis, 2023). A government in this situation is likely to be the target of public anger, and using export restrictions and production subsidies to channel domestic food production into storage may be a precaution against such a scenario.

Export restrictions and expansion of public food stockholdings were in fact a common response to rising food prices during the 2007–2008 financial crisis (Demeke et al., 2014; Headey & Fan, 2010; Sharma, 2011) and played an important role in exacerbating the crisis by amplifying spikes in food prices (Headey, 2011; Headey & Fan, 2010; Sharma, 2011). Although the number of export bans declined as the crisis subsided, the event motivated efforts in many countries to accumulate food reserves that could be drawn upon should a future crisis erupt (Demeke et al., 2014; Margulis, 2014). More recently, extreme weather and disruption of food trade associated with Russia's invasion of Ukraine have led to renewed food export restrictions. For example, India banned wheat exports in 2022 (Akter, 2022) and banned exports of non-basmati rice in 2023 (Biswas, 2023). Some have argued that, in light of climate change induced food price volatility, the World Trade Organization (WTO) should allow greater leeway to countries to pursue non-market measures, like production subsidies and public food stockholdings (Hopewell & Margulis, 2023).

However, food export restrictions have clear systemic shortcomings. They can lead to higher global prices and missed economic opportunities for domestic producers (Akter, 2022; Cardwell & Kerr, 2014; Diao & Kennedy, 2016; Djuric et al., 2015; Götz et al., 2013; Headey, 2011; Makombe & Kropp, 2016; Porteous, 2017). Higher food prices and reduced income for agricultural producers can increase food security risks, especially within low-income, food importing countries (Anderson, 2022). In addition, countries that implement food export bans typically wish to continue importing food from abroad. For example, during the 2007/2008 crisis, export bans were often accompanied by reduced tariffs and duties on food imports (Demeke et al., 2014). Yet by raising prices, export restrictions reduce the effectiveness of international trade as a safeguard of food security, and can thus encourage other countries to impose restrictions of their own and stockpile domestic production. Without measures to stabilize markets and discourage export bans, such a process could ultimately lead to substantial reductions of international food trade. That in turn could leave countries heavily reliant on domestic food production and reserves that might be insufficient to meet the needs of their populations.

National food stockpiles also face a dynamic of diminishing returns as climate impacts intensify, even for countries whose domestic food production makes such an undertaking possible. The increased probability of more frequent and longer lasting food shocks would require ever larger stores held for longer periods of time. Yet such an undertaking would face diminishing returns from negative externalities of scale. Larger food stockpiles carry greater risks of artificially increased prices and wastage (Hopewell & Margulis, 2023). So, persistently intensifying climate impacts on agriculture create collapse risks for national food storage schemes.

In sum, intensifying climate change suggests a dilemma for global food security. On the one hand, while international food trade is essential, trade alone does not adequately address supply shocks that can lead to price spikes and instigate a cascade of export restrictions. On the other, nationally held food stockpiles face diminishing returns because they generate negative externalities that rise with scale. Thus, our approach suggests that other adaptive strategies should be sought.

We suggest, first, that reducing economic inequality is central to the sustainable adaptation of food systems as climate change intensifies. While globalization has reduced inequality *between* countries, it has also coincided with an increase of inequality *within* countries (Heimberger, 2020). Conjoined with increased volatility in agricultural production due to climate change, this inequality is a threat to food security and political stability. A variety of authors have suggested measures aimed at alleviating domestic economic inequalities as important elements of food security (Anderson, 2022; Demeke et al., 2014; Headey & Fan, 2010; Myers et al., 2022). Our point is to link such proposals to adaptive pathways that reduce risks of diminishing returns and collapse. There is, after all, an obvious connection between food security and collapse. Given our definition, societies collapse when they lack capacity to meet basic needs of the population, and food is one such need. Thus, reducing economic inequalities would, other things being equal, curtail collapse risks related to food insecurity. As Middleton (2017) writes, "collapse cautions us to build fair and inclusive societies that minimise room for disaffection and for potentially harmful divisions to arise" (p. 341).

A second suggestion is that internationally held food reserves may be an important adaptation against synchronous crop failures in multiple bread baskets (Myers et al., 2022). Some regional food reserves have already been established (Kumar & George, 2020), such as the Asean Plus Three Emergency Rice Reserve, whose membership consists of South East Asian countries together with China, Japan, and South Korea (Asean Plus Three Emergency Rice Reserve, 2023). Food reserves can be used to provide emergency relief as well as to stabilize prices (Rahman et al., 2020, p. 114). Ideally, international food reserves would mitigate food security risks as well as reducing the total amount of food that would need to be held in reserve compared to a situation in which each country relied on its own separate reserve. In practice, however, regional food reserves face challenges, including accumulating adequate stockpiles, clearly defining the conditions in which food should be released, and establishing effective and independent management of the stocks (Demeke et al., 2014; Rahman et al., 2020). In addition, Hasegawa et al. (2021) find a mismatch between where the largest food reserves are currently held–China and the United States–and where they would be most needed–South Asia. Globally administered food reserves, managed for instance through the United Nations, might be a solution to such imbalances.

These two suggestions connect to our theme of avoiding diminishing returns on adaptation to intensifying climate impacts. They do so by reducing vulnerability to supply shocks without encouraging export bans and hoarding domestic food production. Economic equality and managing food reserves regionally (or globally) creates potential for greater efficiency by enabling food to flow more easily to those who need it and reducing the size of the stockpile each country must accumulate. The creation of internationally held food reserves, however, is a good example of Tainter's idea that solving problems can involve increased sociopolitical complexity, which itself may be subject to diminishing returns. That observation, along with difficulties that have confronted efforts to establish regional food reserves (Demeke et al., 2014; Rahman et al., 2020), suggests that international food reserves should arise incrementally and in response to need. Nevertheless, we suggest that they are an important adaptation to consider given risks to food production related to climate change.

5. Conclusions

A forward-looking approach should explain how collapse risks can be studied as they develop and should suggest adaptation strategies for reducing those risks. We suggest the following postulates for a forward-looking approach: (1) collapse, if it occurs, is likely to be a lengthy process rather than an abrupt event; (2) significant collapse risks are already present in some places; and (3) diminishing returns on adaptation to intensifying climate impacts may be a driver of collapse risks. Given the first two of these postulates, risks of climate collapse can be studied in the present. And the third postulate suggests that avoiding pathways that entail unsustainable diminishing returns is an important consideration for adaptation to climate change.

Our approach also makes theoretical contributions to research on societal collapse. We apply diminishing returns to climate change adaptation, rather than to sociopolitical complexity (Tainter, 1988) or resource extraction (Bardi et al., 2019). Consequently, our proposal can more simply explain collapse risks in small states with negligible greenhouse gas emissions, such as Tuvalu. Moreover, we explain how international cooperation in food trade can be threatened by climate change in ways that may lead to a pathway of diminishing returns and collapse risks. And finally, our approach emphasizes that while collapse risks should be taken seriously, collapse itself is not inevitable. It is possible to choose a sustainable path if we know the way.

Research ethics

This article does not contain any studies with human or animal participants performed by any of the authors.

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