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Existential risk due to ecosystem collapse: Nature strikes back

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ABSTRACT

Epic tales of existential catastrophe have been written down for thousands of years, and in Christian traditions were linked to the punishment of humanity for its sins. We are still imagining new storylines for the end-of-civilization, with a rich genre of Hollywood films depicting either the struggles of remnant humans in a post-apocalyptic world, or some event that threatens the very survival of our species. Instead of a spiritual reckoning imposed by God, Hollywood's Armageddon is usually the result of technology run amok, or mindless industrialization and population growth causing an environmental collapse. While dramatization of an environmental Armageddon might seem fanciful, existential risk warrants serious consideration even though the probability of an apocalypse is vanishingly small. If we are to avoid the unthinkable and unimaginable, then we need to ask what might be the most plausible pathways to an environmental apocalypse? We review the major environmental concepts pertinent to apocalyptic events, and conclude that positive feedback loops and multiplicative stresses represent the gravest existential risks, and the risks society is least likely to foresee. Zombies created by a misbegotten genetically engineered virus might make for a great movie, but it is the hubris of technical experts who are blind to surprising interaction networks, or who are unaware of positive feedback loops that will be our undoing.

1. Introduction: ancient apocalyptic narratives

The notion of existential catastrophes that either end the world or destroy civilization can be traced back to some of the earliest flood myths, including the Epic of Gilgamesh and the great flood in the Book of Genesis. Christian tradition foresees Armageddon as a final spiritual reckoning, or a battle between God and the armies of unrepentant sinners. In more recent times, the possibility of an apocalyptic future for humanity has been linked to over-population and exceeding the world's food supply. Thomas Malthus is credited with best articulating a future of global famine, when he wrote in 1798, "*the power of population is so superior to the power of the earth to produce subsistence for man, that premature death must in some shape or other visit the human race*" (Malthus, 2003). But it is only within the last fifty years that scenarios of global or regional collapse have been scientifically linked to our understanding of ecology and ecosystem science.

Whereas Malthus foresaw collapse due to a simple shortage of food, advances in ecology have made it clear that disruptions of ecological processes, or unforeseen impacts of pollution on human health, pose threats to our existence. Rachel Carson's pioneering book, *Silent Spring*, documented massive declines in bird populations associated with DDT and raised the specter of threatened human health, thereby ushering in the formation of the Environmental Protection Agency (EPA), and an effective regulatory response to air and water pollution. Many parts of the world have now cleaned up their air and water (Butt et al., 2017; Garmo et al., 2014), and it is clear we have the technology to do so everywhere if there is sufficient political will and funding. But recently subtler and more

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pervasive existential threats have emerged for the world's ecosystem. One risk is the "extinction crisis" or "sixth great extinction" being driven by man (Barnosky et al., 2011). Here the threat is that if we lose too much biodiversity, essential ecological processes will be undermined to such an extent that our food and water supplies could be interrupted, natural hazards and epidemics exacerbated, climate regulation disturbed, and the fertility of soil reduced (Díaz, Fargione, & Tilman, 2006). The biodiversity crisis is one dimension of a more comprehensive view of our planet, which hypothesizes the presence of several physical and ecological boundaries that, if exceeded, put at risk our civilization (Rockström, Steffen, Noone, & Persson, 2009). These planetary boundaries are defined by limits to: land-use change, biodiversity loss, nitrogen removed for human use, phosphorous cycle disruption, freshwater use, atmospheric aerosol loading, chemical pollution, climate change, ocean acidification, and ozone depletion (Rockström et al., 2009).

While there is no doubt that the future scenarios sketched by Malthus, Rachel Carson, and Rockström, among many other environmental visionaries, could yield unacceptable environmental degradation, it is not clear what environmental pathways would be catastrophic in the existential sense of ending civilization as we know it—either regionally or globally. We focus in this article on identifying those ecological scenarios that we can imagine producing apocalyptic havoc. Before examining the science it is worth reflecting on the end-of-world futures that have captured the imagination of popular culture.

2. What does popular culture tell us about environmental catastrophes and existential risk?

Popular culture can often provide insight into a generation's socio-political concerns, fears, and anxieties (Jones, Mccarthy, & Murphy, 2011). Films depicting global catastrophes and apocalyptic scenarios have been around for decades, and involve a wide range scenarios, from Earth-dominating aliens, robots destroying mankind, to famine-ridden worlds. Disaster films also include themes about environmental collapses which can include a future world with rising sea levels (e.g., *Waterworld*), extreme climatic events (e.g., *The Day After Tomorrow*), or chemical or radioactive contamination (e.g., *The China Syndrome*). Culture, technology, and science do not occupy separate worlds—indeed it is the entanglement of these human endeavors that shape both the future, and our response to potential existential risks (Latour, 2011). For that reason there is merit in examining popular culture and its rendition of ecocatastrophes.

2.1. Methodology to explore the most successful films about catastrophe

To systematically examine Hollywood's vision of epic disasters and environmental Armageddon, we analyzed the highest grossing films between 1956 and 2016. We selected this interval to capture films both before and after the publication of Rachel Carson's *Silent Spring* (published in 1962), which was a watershed moment in American environmentalism. We identified the highest grossing films per year and flagged each of those popular films that fell into either of two main categories: environmental collapse or disaster. We made a distinction between disaster films and environmental collapse films to separate apocalyptic events due to technology run amok, alien invasions, earthquakes, etc. from apocalyptic futures due to human inflicted damage to the environment that comes back to harm humans. Obviously an "alien invasion" damages the environment, but it does not happen because of a disregard for maintaining a healthy environment. In most (all but 4 of 60) years, our "top grossing" category represented a top twenty list.

2.2. Major themes in disaster and environmental collapse films

Since 1956, there have been ten apocalyptic films with an environmental theme that qualify as top box office hits. Prior to 1956 we could not identify any popular environmentally-themed catastrophe films. In fact, all ten of the top grossing environmental films appeared after 1975 and hence after the emergence of a strong environmental movement in the U.S.; there is a hint of an increase in their frequency through time (Fig. 1a). In contrast, the fifty-nine top grossing disaster films span the entire 1956–2016 interval (Fig. 1b), and we know of several disaster films that were popular successes long before 1956, although box office data were less reliable. For example, a huge hit with audiences in 1916 entitled *The End of the World*, had as its cause a comet that passed too close to the planet and showered fiery sparks down upon people creating social unrest and earthbound natural disasters. The film *Deluge* in 1933 was a Hollywood success that depicted worldwide natural disasters in the form of days of unending earthquakes.

Modern films portraying end-of-civilization scale disasters include alien invasions, plagues caused by genetically engineered viruses, malignant artificial intelligence, earthquakes and tidal waves, global war, and technical accidents. Variations of core themes in the disaster film genre essentially continue to repeat themselves since the late 1950s. For example, scripts about mutated monsters and zombies produced several box office hits in the late 1950s and 1960s with movies such as *Godzilla Raids Again* (1959) and *Night of the Living Dead* (1968), and similar stories yielded more recent successful films like *Godzilla* (1998 and 2014) and the zombie-crazed *World War Z* (2013). Hollywood films about alien invasions have made it among the top box office films every decade since the 1970s—notable alien invasion movies include *The Andromeda Strain* (1971), *Independence Day* (1996) and *War of the Worlds* (2005)—all of which attracted large audiences. An additional disaster theme entails nuclear war as portrayed in movies such as *Dr. Strangelove or: How I Learned to Stop Worrying and Love the Bomb* (1964) and *On the Beach* (1959).

Technology run amok is an especially popular theme in disaster films. Billion dollar franchises like *The Terminator* and *The Matrix* came to prominence with depictions of a future in which highly intelligent machines wage a war against the human species that created them. The audience appeal of "technology rebelling" is particularly evident in the commercial success of the *Jurassic Park* series, which with a revenue of $5 billion is among the highest grossing movie franchises of all time. Although the *Jurassic Park* series does not entail a major environmental catastrophe, it is an adventure story of human lives at risk because of misbehaving genetically

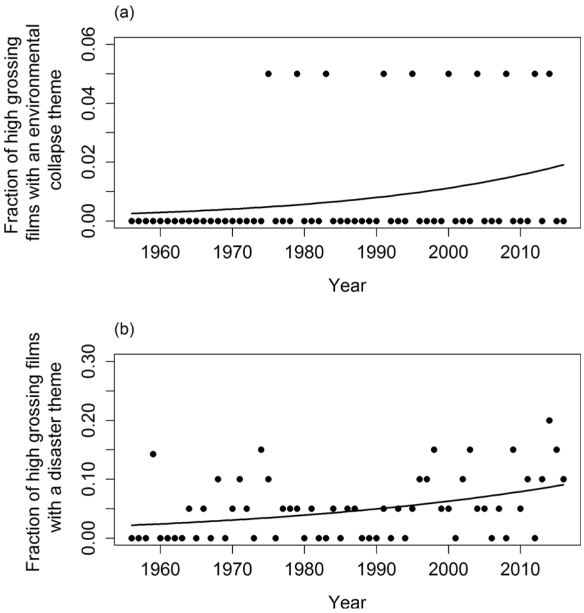

Fig. 1. (a) Fraction of the highest grossing films with an environmental collapse theme. (b) Fraction of the highest grossing films with either an environmental collapse or disaster theme. The regression lines represent the fraction of highest grossing films (by type) per year fitted to a logistic regression model. All fractions based on top twenty grossing films except for the following years (with the number of films on which percentage was based in parentheses): 1958 (10), 1959 (14), 1960 (10), 1961 (14). Please see Supplementary material for data used in this logistic regression model.

engineered dinosaurs.

Whereas general disaster films are diverse in their premises, films of environmental catastrophe are primarily stories about either corporate greed or flawed societal norms. For example, four of the ten environmental catastrophe movies in Table 1 revolve around corporations knowingly polluting the environment or shirking environmental precautions for the sake of profit (The China Syndrome, Silkwood, Erin Brockovich, and Dr. Seuss' The Lorax). These films are less about the environment than they are films about evil corporate behavior. The remaining six environmental disaster films paint a picture of an unlivable dystopian planet that has been gradually degraded by a myopic society that could not take action to avert environmental catastrophe. Notably, none of the environmental disaster films draw on any insights from environmental science or ecology, such as the planetary boundaries framework. Hollywood emphasizes greed and misguided society as opposed to the dangers of ignorance and unwittingly exceeding a critical environmental threshold that science has failed to document and specify. In Hollywood, environmental disasters are the consequence of human failings, and not the consequence of ignorance or major gaps in scientific understanding.

We do not want to imply that economic systems or human selfishness are unimportant. There is no question that great harm has been and is being done by what we can only call criminal behavior—either violating existing environmental regulations or lobbying against the passage of regulations even though scientific evidence of harm is compelling. We acknowledge the presence of such behavior, but argue that an engaged public and effective government can mitigate these threats in time to avert global disasters. In contrast, no amount of public engagement or effective governance can mitigate threats that are unknown or underestimated.

Below we draw on the scientific literature to argue that it is our ignorance about the dynamics of complex, tightly coupled, human-natural systems with interacting stresses and feedback loops that is the source of our greatest environmentally-dictated existential risk. While we recognize the failings of human nature, it is the possible failure of science to anticipate the vigor of positive feedback loops or to recognize how different environmental perturbations can amplify one another, that gives us our greatest concern.

3. Which of the planetary boundaries correspond to true existential risk?

Johan Rockström and colleagues have identified nine planetary boundaries, which "*if crossed could have disastrous consequences for humanity*" (Rockström et al., 2009). Conversely, if the planet is stewarded in a way that the boundaries are not crossed it is considered to be in a safe space. One of the planetary boundaries entails atmospheric CO_2, with the proposed boundary being 350 ppm, which of course we have already crossed. While there is no solid evidence that in fact 350 ppm is a threshold across which existential risk increases, there is little doubt that at some point greatly elevated CO_2 atmospheric concentrations might trigger a series of events that could indeed produce apocalyptic outcomes for humanity (Van Aalst, 2006). These could include changing major ocean circulation patterns, causing massive sea level rise, and increasing the frequency and severity of extreme events (e.g., droughts, storms, floods) that displace people, and ruin economies.

The interesting question is whether any of the planetary thresholds other than CO_2 could also portend existential risks. Here the answer is not clear. One boundary often mentioned as a concern for the fate of global civilization is biodiversity (Ehrlich & Ehrlich,

Table 1
Films with an environmental collapse theme from the sample of top grossing films from 1956 to 2016. Each film was assigned a planetary boundary based on its plot. Note: The Rank in Top Box Office column corresponds to the film's ranking in its year of release.

Environmental Collapse Film	Year Released	Rank in Top Box Office	Plot	Planetary Boundary
The Adventures of the Wilderness Family	1975	14	Smog and congestion drives a family to flee the city	Atmospheric aerosol loading
The China Syndrome	1979	12	An unsafe nuclear power plant continues to operate	Chemical pollution
Silkwood	1983	19	A factory of plutonium fuel rods exposes workers to radiation	Chemical pollution
Star Trek VI: The Undiscovered Country	1991	15	Explosion of the moon leads to impending ozone layer depletion	Stratospheric ozone depletion
Waterworld	1995	12	Polar ice caps melt and rising sea levels submerge continents underwater	Climate change
Erin Brockovich	2000	13	A corporation illegally dumps toxic waste and pollutes water supply	Chemical pollution
The Day After Tomorrow	2004	7	Catastrophic climatic events usher global cooling and lead to a new ice age	Climate change
Wall-E	2008	5	A lonely robot is left behind to clean up a trash-ridden Earth	Chemical pollution
Dr. Seuss' The Lorax	2012	11	A greedy businessman destroys natural land and creates an artificial world	Change in land use
Interstellar	2014	16	Natural disasters, crop blights, and drought on Earth force humans to search for a new home in outer space	Climate change

2012), with the proposed safety threshold being a loss of greater than 0.001% per year (Rockström et al., 2009). There is little evidence that this particular 0.001% annual loss is a threshold—and it is hard to imagine any data that would allow one to identify where the threshold was (Brook, Ellis, Perring, Mackay, & Blomqvist, 2013; Lenton & Williams, 2013). A better question is whether one can imagine any scenario by which the loss of too many species leads to the collapse of societies and environmental disasters, even though one cannot know the absolute number of extinctions that would be required to create this dystopia.

While there are data that relate local reductions in species richness to altered ecosystem function, these results do not point to substantial existential risks. The data are small-scale experiments in which plant productivity, or nutrient retention is reduced as species numbers decline locally (Vellend, 2017), or are local observations of increased variability in fisheries yield when stock diversity is lost (Schindler et al., 2010). Those are not existential risks. To make the link even more tenuous, there is little evidence that biodiversity is even declining at local scales (Vellend et al., 2013, 2017). Total planetary biodiversity may be in decline, but local and regional biodiversity is often staying the same because species from elsewhere replace local losses, albeit homogenizing the world in the process. Although the majority of conservation scientists are likely to flinch at this conclusion, there is growing skepticism regarding the strength of evidence linking trends in biodiversity loss to an existential risk for humans (Maier, 2012; Vellend, 2014). Obviously if all biodiversity disappeared civilization would end—but no one is forecasting the loss of all species. It seems plausible that the loss of 90% of the world's species could also be apocalyptic, but not one is predicting that degree of biodiversity loss either. Tragic, but plausible is the possibility of our planet suffering a loss of as many as half of its species. If global biodiversity were halved, but at the same time locally the number of species stayed relatively stable, what would be the mechanism for an end-of-civilization or even end of human prosperity scenario? Extinctions and biodiversity loss are ethical and spiritual losses, but perhaps not an existential risk.

What about the remaining eight planetary boundaries? Stratospheric ozone depletion is one—but thanks to the Montreal Protocol ozone depletion is being reversed (Hand, 2016). Disruptions of the nitrogen cycle and of the phosphorous cycle have also been proposed as representing potential planetary boundaries (one boundary for nitrogen and one boundary for phosphorous). There are compelling data linking excesses in these nutrients to environmental damage. For example, over-application of fertilizer in Midwestern USA has led to dead zones in the Gulf of Mexico. Similarly, excessive nitrogen has polluted groundwater in California to such an extent that it is unsuitable for drinking and some rural communities are forced to drink bottled water. However, these impacts are local. At the same time that there is too much N loading in the U.S., there is a need for more N in Africa as a way of increasing agricultural yields (Mueller et al., 2012). While the disruption of nitrogen and phosphorous cycles clearly perturb local ecosystems, end-of-the-world scenarios seem a bit far-fetched.

Another hypothesized planetary boundary entails the conversion of natural habitats to agricultural land. The mechanism by which too much agricultural land could cause a crisis is unclear—unless it is because land conversion causes so much biodiversity loss that species extinctions are the proximate cause of an ecocatastrophe. Excessive chemical pollution and excessive atmospheric aerosol loading have each been suggested as planetary boundaries as well. In the case of these pollution boundaries, there are well-documented mechanisms by which surpassing some concentration of a pollutant inflicts severe human health hazards. There is abundant evidence linking chemical and aerosol pollution to higher mortality and lower reproductive success in humans, which in turn could cause a major die-off. It is perhaps appropriate then that when Hollywood envisions an unlivable world, it often invokes a story of humans poisoning themselves. That said, it is doubtful that we will poison ourselves towards extinction. Data show that as nations develop and increase their wealth, they tend to clean up their air and water and reduce environmental pollution (Flörke et al., 2013; Hao & Wang, 2005). In addition, as economies become more circular (see Mathews & Tan, 2016), environmental damage due to waste products is likely to decline. The key point is that the pollutants associated with the planetary boundaries are so widely recognized, and the consequences of local toxic events are so immediate, that it is reasonable to expect national governments to act before we suffer a planetary ecocatastrophe.

In summary, six of the nine proposed planetary boundaries (phosphorous, nitrogen, biodiversity, land use, atmospheric aerosol loading, and chemical pollution) are unlikely to be associated with existential risks. They all correspond to a degraded environment, but in our assessment do not represent existential risks. However, the three remaining boundaries (climate change, global freshwater cycle, and ocean acidification) do pose existential risks. This is because of intrinsic positive feedback loops, substantial lag times between system change and experiencing the consequences of that change, and the fact these different boundaries interact with one another in ways that yield surprises. In addition, climate, freshwater, and ocean acidification are all directly connected to the provision of food and water, and shortages of food and water can create conflict and social unrest.

Climate change has a long history of disrupting civilizations and sometimes precipitating the collapse of cultures or mass emigrations (McMichael, 2017). For example, the 12th century drought in the North American Southwest is held responsible for the collapse of the Anasazi pueblo culture. More recently, the infamous potato famine of 1846–1849 and the large migration of Irish to the U.S. can be traced to a combination of factors, one of which was climate. Specifically, 1846 was an unusually warm and moist year in Ireland, providing the climatic conditions favorable to the fungus that caused the potato blight. As is so often the case, poor government had a role as well—as the British government forbade the import of grains from outside Britain (imports that could have helped to redress the ravaged potato yields).

Climate change intersects with freshwater resources because it is expected to exacerbate drought and water scarcity, as well as flooding. Climate change can even impair water quality because it is associated with heavy rains that overwhelm sewage treatment facilities, or because it results in higher concentrations of pollutants in groundwater as a result of enhanced evaporation and reduced groundwater recharge. Ample clean water is not a luxury—it is essential for human survival. Consequently, cities, regions and nations that lack clean freshwater are vulnerable to social disruption and disease.

Finally, ocean acidification is linked to climate change because it is driven by CO_2 emissions just as global warming is. With close to 20% of the world's protein coming from oceans (FAO, 2016), the potential for severe impacts due to acidification is obvious. Less obvious, but perhaps more insidious, is the interaction between climate change and the loss of oyster and coral reefs due to acidification. Acidification is known to interfere with oyster reef building and coral reefs. Climate change also increases storm frequency and severity. Coral reefs and oyster reefs provide protection from storm surge because they reduce wave energy (Spalding et al., 2014). If these reefs are lost due to acidification at the same time as storms become more severe and sea level rises, coastal communities will be exposed to unprecedented storm surge—and may be ravaged by recurrent storms.

A key feature of the risk associated with climate change is that mean annual temperature and mean annual rainfall are not the variables of interest. Rather it is extreme episodic events that place nations and entire regions of the world at risk. These extreme events are by definition "rare" (once every hundred years), and changes in their likelihood are challenging to detect because of their rarity, but are exactly the manifestations of climate change that we must get better at anticipating (Diffenbaugh et al., 2017). Society will have a hard time responding to shorter intervals between rare extreme events because in the lifespan of an individual human, a person might experience as few as two or three extreme events. How likely is it that you would notice a change in the interval between events that are separated by decades, especially given that the interval is not regular but varies stochastically? A concrete example of this dilemma can be found in the past and expected future changes in storm-related flooding of New York City. The highly disruptive flooding of New York City associated with Hurricane Sandy represented a flood height that occurred once every 500 years in the 18th century, and that occurs now once every 25 years, but is expected to occur once every 5 years by 2050 (Garner et al., 2017). This change in frequency of extreme floods has profound implications for the measures New York City should take to protect its infrastructure and its population, yet because of the stochastic nature of such events, this shift in flood frequency is an elevated risk that will go unnoticed by most people.

4. The combination of positive feedback loops and societal inertia is fertile ground for global environmental catastrophes

Humans are remarkably ingenious, and have adapted to crises throughout their history. Our doom has been repeatedly predicted, only to be averted by innovation (Ridley, 2011). However, the many stories of human ingenuity successfully addressing existential risks such as global famine or extreme air pollution represent environmental challenges that are largely linear, have immediate consequences, and operate without positive feedbacks. For example, the fact that food is in short supply does not increase the rate at which humans consume food—thereby increasing the shortage. Similarly, massive air pollution episodes such as the London fog of 1952 that killed 12,000 people did not make future air pollution events more likely. In fact it was just the opposite—the London fog sent such a clear message that Britain quickly enacted pollution control measures (Stradling, 2016). Food shortages, air pollution, water pollution, etc. send immediate signals to society of harm, which then trigger a negative feedback of society seeking to reduce the harm.

In contrast, today's great environmental crisis of climate change may cause some harm but there are generally long time delays between rising CO_2 concentrations and damage to humans. The consequence of these delays are an absence of urgency; thus although 70% of Americans believe global warming is happening, only 40% think it will harm them (http://climatecommunication.yale.edu/visualizations-data/ycom-us-2016/). Secondly, unlike past environmental challenges, the Earth's climate system is rife with positive feedback loops. In particular, as CO_2 increases and the climate warms, that very warming can cause more CO_2 release which further increases global warming, and then more CO_2, and so on. Table 2 summarizes the best documented positive feedback loops for the Earth's climate system. These feedbacks can be neatly categorized into carbon cycle, biogeochemical, biogeophysical, cloud, ice-albedo, and water vapor feedbacks. As important as it is to understand these feedbacks individually, it is even more essential to study the interactive nature of these feedbacks. Modeling studies show that when interactions among feedback loops are included, uncertainty increases dramatically and there is a heightened potential for perturbations to be magnified (e.g., Cox, Betts, Jones, Spall, & Totterdell, 2000; Hajima, Tachiiri, Ito, & Kawamiya, 2014; Knutti & Rugenstein, 2015; Rosenfeld, Sherwood, Wood, & Donner, 2014). This produces a wide range of future scenarios.

Positive feedbacks in the carbon cycle involves the enhancement of future carbon contributions to the atmosphere due to some initial increase in atmospheric CO_2. This happens because as CO_2 accumulates, it reduces the efficiency in which oceans and terrestrial ecosystems sequester carbon, which in return feeds back to exacerbate climate change (Friedlingstein et al., 2001). Warming can also increase the rate at which organic matter decays and carbon is released into the atmosphere, thereby causing more warming (Melillo et al., 2017). Increases in food shortages and lack of water is also of major concern when biogeophysical feedback mechanisms perpetuate drought conditions. The underlying mechanism here is that losses in vegetation increases the surface albedo, which suppresses rainfall, and thus enhances future vegetation loss and more suppression of rainfall—thereby initiating or prolonging a drought (Chamey, Stone, & Quirk, 1975). To top it off, overgrazing depletes the soil, leading to augmented vegetation loss (Anderies, Janssen, & Walker, 2002).

Climate change often also increases the risk of forest fires, as a result of higher temperatures and persistent drought conditions. The expectation is that forest fires will become more frequent and severe with climate warming and drought (Scholze, Knorr, Arnell, & Prentice, 2006), a trend for which we have already seen evidence (Allen et al., 2010). Tragically, the increased severity and risk of Southern California wildfires recently predicted by climate scientists (Jin et al., 2015), was realized in December 2017, with the largest fire in the history of California (the "*Thomas fire*" that burned 282,000 acres, https://www.vox.com/2017/12/27/16822180/thomas-fire-california-largest-wildfire). This catastrophic fire embodies the sorts of positive feedbacks and interacting factors that could catch humanity off-guard and produce a true apocalyptic event. Record-breaking rains produced an extraordinary flush of new vegetation, that then dried out as record heat waves and dry conditions took hold, coupled with stronger than normal winds, and ignition. Of course the record-fire released CO_2 into the atmosphere, thereby contributing to future warming.

Table 2
A set of examples of positive feedbacks influencing the earth-atmosphere system.

Positive Feedback Mechanisms	
Carbon cycle/biogeochemical/biogeophysical feedbacks	
Carbon enhancement	Climate warming induces the release and amplification of carbon in the atmosphere through numerous mechanisms (e.g., decreased land and ocean carbon sink efficiency, microbial stimulation of old soil, thawing permafrost and gas hydrates), further amplifying global warming (Friedlingstein et al., 2001; Heimann & Reichstein, 2008; Lashof, 1989; Zimov et al., 2006).
Forest fire frequency	Rising temperatures, drought, and deforestation contribute to higher forest fire frequency, severity, and vulnerability, which releases more CO_2 into the atmosphere and causes further global warming (Laurance & Williamson, 2001; Scholze et al., 2006).
Poleward biome shifts	Based on paleo studies, anthropogenic warming may induce a poleward shift of boreal forest into tundra, decreasing surface albedo and therefore trapping more heat (Lashof et al., 1997).
Changes in vegetation albedo	Losses in vegetation cover increases surface albedo, reduces tendency for rainfall and the loss of soil and soil nutrients, and thus enhances plant cover loss (Chamey et al., 1975).
Aerosols	An enhancement of anthropogenic aerosols contribute to large concentrations of small cloud condensation nuclei, which form high concentration of small cloud droplets, therefore suppressing rainfall. The decrease in precipitation amplifies aerosol loading (Zhao, Tie, & Lin, 2006).
Tropospheric ozone	Higher tropospheric ozone concentrations reduces plant photosynthesis and is responsible for a reduction dry deposition velocity and rise in isoprene emissions, thereby decreasing the land-carbon sink and enhancing surface ozone (Sitch, Cox, Collins, & Huntingford, 2007).
Release of greenhouse gases from oceans	Models show that in a future warmer climate (4000 CE), production of calcium carbonate in the surface ocean and denitrification in the water column increases, enhancing concentrations of nitrous oxide and pCO_2 in the surface ocean and atmosphere, further trapping heat (Schmittner, Oschlies, Matthews, & Galbraith, 2008).
Cloud feedbacks	
Changes in cloud amount	Modeling and observational studies show that changes in the type of cloud amount can have potential positive feedback impacts, amplifying climate warming (Bellomo, Clement, Murphy, Polvani, & Cane, 2016; Bony et al., 2016; Boucher et al., 2013; Cess et al., 1990; Clement et al., 2009; Huo & Lu, 2014; Yuan et al., 2016; Zhou, Dessler, Zelinka, Yang, & Wang, 2014).
Ice-albedo feedback	
Receding snow and ice	A decrease in areal cover of snow and ice leads to an increase in surface temperature, which then further decreases areal cover of snow and ice (Curry et al., 1995).
Water vapor feedback	
Water vapor enhancement	Warmer atmospheric conditions increase saturation vapor pressure, further driving warmer temperatures in the atmosphere by the amplifying climatic effects of water vapor (Manabe & Wetherald, 1967).

Out of all types of feedbacks, water vapor and the ice-albedo feedbacks are the most clearly understood mechanisms. Losses in reflective snow and ice cover drive up surface temperatures, leading to even more melting of snow and ice cover—this is known as the ice-albedo feedback (Curry, Schramm, & Ebert, 1995). As snow and ice continue to melt at a more rapid pace, millions of people may be displaced by flooding risks as a consequence of sea level rise near coastal communities (Biermann & Boas, 2010; Myers, 2002; Nicholls et al., 2011). The water vapor feedback operates when warmer atmospheric conditions strengthen the saturation vapor pressure, which creates a warming effect given water vapor's strong greenhouse gas properties (Manabe & Wetherald, 1967).

Global warming tends to increase cloud formation because warmer temperatures lead to more evaporation of water into the atmosphere, and warmer temperature also allows the atmosphere to hold more water. The key question is whether this increase in clouds associated with global warming will result in a positive feedback loop (more warming) or a negative feedback loop (less warming). For decades, scientists have sought to answer this question and understand the net role clouds play in future climate projections (Schneider et al., 2017). Clouds are complex because they both have a cooling (reflecting incoming solar radiation) and warming (absorbing incoming solar radiation) effect (Lashof, DeAngelo, Saleska, & Harte, 1997). The type of cloud, altitude, and optical properties combine to determine how these countervailing effects balance out. Although still under debate, it appears that in most circumstances the cloud feedback is likely positive (Boucher et al., 2013). For example, models and observations show that increasing greenhouse gas concentrations reduces the low-level cloud fraction in the Northeast Pacific at decadal time scales. This then has a positive feedback effect and enhances climate warming since less solar radiation is reflected by the atmosphere (Clement, Burgman, & Norris, 2009).

The key lesson from the long list of potentially positive feedbacks and their interactions is that runaway climate change, and runaway perturbations have to be taken as a serious possibility. Table 2 is just a snapshot of the type of feedbacks that have been identified (see Supplementary material for a more thorough explanation of positive feedback loops). However, this list is not exhaustive and the possibility of undiscovered positive feedbacks portends even greater existential risks. The many environmental crises humankind has previously averted (famine, ozone depletion, London fog, water pollution, etc.) were averted because of political will based on solid scientific understanding. We cannot count on complete scientific understanding when it comes to positive feedback loops and climate change.

5. It is multiplicative stresses (or "double whammies") that should be our greatest concern

It is easy to see how positive feedback loops exacerbate existential risks. A second, but less obvious danger is the linkage of seemingly unrelated processes or phenomenon that increase risk. A good example is wildfires and tornadoes. Both of these represent natural disasters that can cause great damage. Until recently no one linked these two phenomena, and no one would have imagined that an increase in wildfires might cause an increase in tornados. However, researchers in 2016 documented a linkage between wildfires in Central America and the worst episode of tornadoes in North America's recorded history (Saide et al., 2016)—more than 120 twisters in one day, which killed 316 people. The mechanism is that the aerosol particles produced by wildfires increase the vertical sheer in atmospheric wind speeds, which in turn makes tornadoes more likely and more severe.

While tornadoes and wildfires are both local there are other trends that are national or even global that entail interacting risks factors—or what the renowned ecologist Robert T. Paine called a "double whammy" (Paine, 1993). Paine makes the argument that whereas one perturbation or stress on its own might not be terribly worrisome, if an ecosystem is hit with two stresses or threats at the same time (or in quick succession) the result can be surprisingly catastrophic. For example, aging infrastructure in the United States (dams, bridges, levees, etc.) is often talked about as a disaster waiting to happen (Reid, 2008). Similarly, increased extreme rainfall is widely appreciated as a likely outcome of climate change. Putting the two together, we have a recipe for turning improbable events into something that should be expected. A specific example of what was once a highly unlikely tragedy, but is now perhaps a probable disaster is the failure of a large dam. If large aging dams fail due to the combination of decaying infrastructure and unprecedented rainfall, downstream communities could be destroyed. Existing dams were engineered for flood frequencies and rainfall regimes that have been replaced by much more extreme weather events. This should raise general concerns about flood-safety. Not only are the designs for major dams obsolete due to climate changes, the dams themselves are obsolete. In the United States alone, more than 85% of large dams will be more than 50 years old by 2020 (Hossain et al., 2009). Based on data from the National Performance of Dam Failures, the top ten causes of dam incidents in the United States are depicted in Fig. 2a. The most frequent type of incident was attributed to inflow floods—that is more than 1000 dam failures. The reason this is a global concern is that observations (Fig. 2b) in dry and wet regions all over the world show that extreme precipitation events have been increasing since the 1950s (Donat, Lowry, & Alexander, 2017). The combined effect of intensified rainfall and old dams pose a clear risk to communities worldwide.

California, which has used dams and reservoirs to store water on a massive scale, recently suffered through several consecutive years of both low rainfall and high temperatures that produced a 5-year record-breaking drought (Diffenbaugh, Swain, & Touma, 2015). In early 2017, the state experienced massive amounts of precipitation leading to its wettest rainy season on record (Vahedifard, AghaKouchak, Ragno, Shahrokhabadi, & Mallakpour, 2017). The rainfall unleashed floods, landslides, and nearly collapsed the Oroville Dam, the tallest dam in North America. The tremendous water flows severely damaged the dam's spillways, prompting the evacuation of about 190,000 people downriver of the dam (Park & Mclaughlin, 2017). This particular crisis is an example of how the intersection of climate change and infrastructure that is either aging or that was designed for different conditions can potentially lead to a catastrophe (Vahedifard et al., 2017). With the likelihood of more frequent extreme events in the future, situations like the one experienced at the Oroville Dam will become more common.

The intersection of climate change and human activity is also elevating the risk of severe wildfires in large portions of the world. Models suggest that precipitation was the primary driver behind global fire regimes during the preindustrial era, and then shifted towards an anthropogenic-driven regime during the industrial period (Pechony & Shindell, 2010). Now it appears that temperature will play a strong role in the 21st century in global wildfires (Pechony & Shindell, 2010). The combination of increasing temperatures at the global scale with increased propensity of wildfires due to human activity at the local level could lead to massive infernos (Bonan, 2008). Wildfire severity and frequency will be dramatically increased wherever the mean temperature in a region increases by 3 °C or more; unfortunately, in the Sahel, central Australia, central Asia, southern Africa, the western U.S., and in most of South America, warming is indeed expected to exceed 3 °C (Scholze et al., 2006). This is a global threat.

Sometimes there is irony in the way stresses combine to produce a catastrophe. Humans have adapted to heat waves by installing air conditioning. The combination of a heat wave, with increased demands for irrigation and air conditioning led to the largest ever power outage in India during 2012. Over 600 million were left without electricity and without air conditioning to mitigate the heat wave (Lundgren & Kjellstrom, 2013). Hospitals lost power and cities shut down. While it is possible to improve on the design of electric grids to reduce such massive outages (Fang, 2014), it is clear that the combination of extreme climate events and how humans respond to those heat waves has led to several massive power outages around the world (Klinger & Landeg, 2014). The irony is that air conditioning is an adaptation to heat—and the adoption of air conditioning routinely saves lives (Barreca, Clay, Deschenes, Greenstone, & Shapiro, 2016). But the adaptation that saves human lives can overburden an electric grid and make it much more susceptible to failure. Again it is the interconnections of stresses and the way we respond to environmental shocks that promulgates the greatest existential risk.

6. Can we be smart enough to avoid existential environmental catastrophes?

Two well-understood and much discussed causes of environmental collapse are: 1) over-exploitation of nature to such an extent that there is no longer sufficient natural capital to supply basic human needs (e.g., food and water), and 2) unintended consequences of technology. Over-exploitation of common natural resources has been called the "tragedy of the commons", and a wide variety of public policies and government regulations have been devised to rectify this tragedy. The risks due to technological advances are also in a sense well-understood, or at least widely discussed. Often the "technology" that poses an existential risk is a technology that has been invented to forestall over-exploitation by increasing efficiencies. For example, industrialized agriculture may boost crop yields

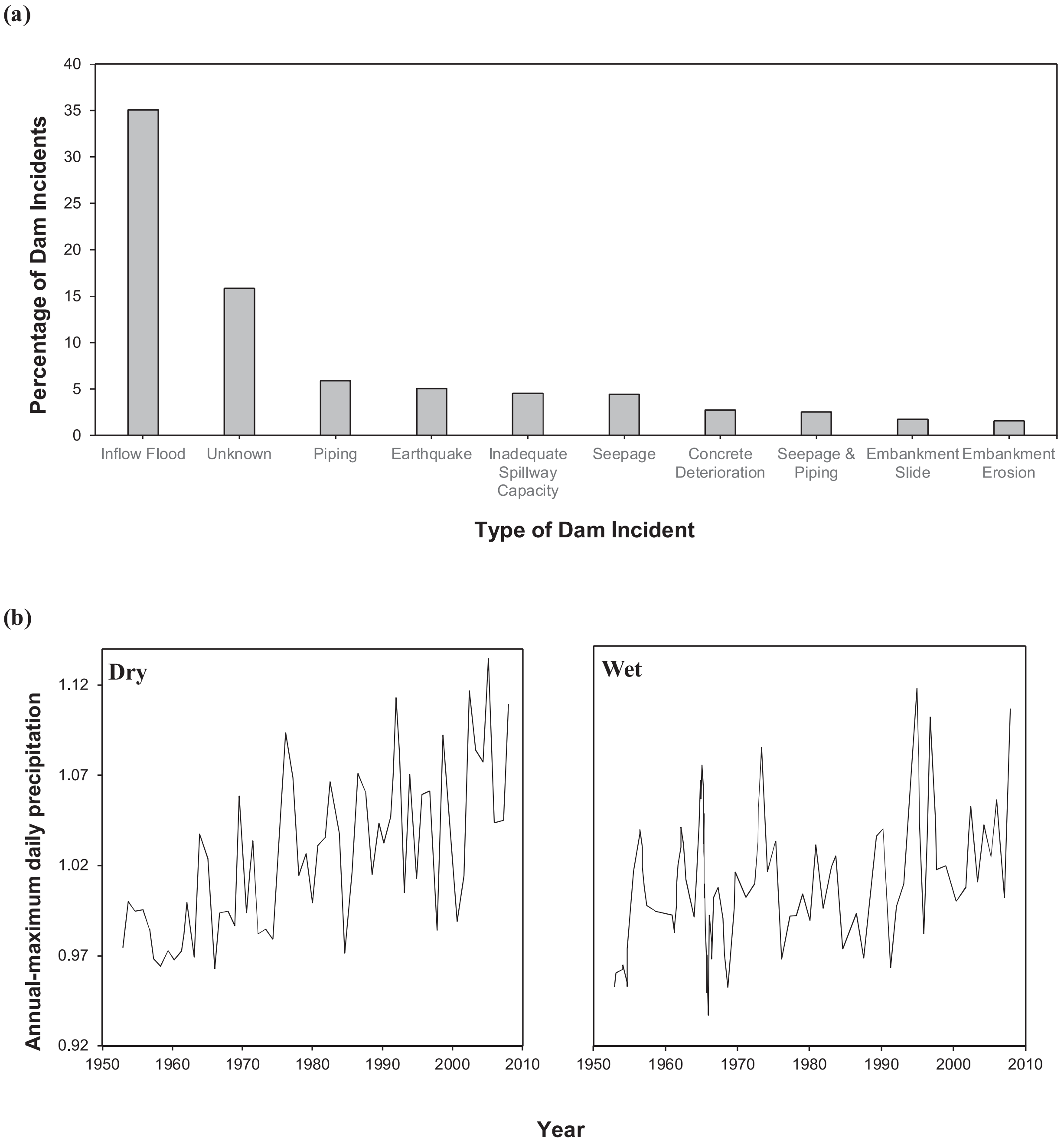

Fig. 2. (a) The percentage of dam incidents by type in the United States from the year 1848 to 2015. This graph shows only the top 10 most frequent causes of dam failures from a total of 308 types of incidents. The data was collected from the National Performance of Dam Failures at Stanford University. (b) The maximum rainfall in a one-day period recorded for each year, averaged across all observations in dry and wet regions.
This figure was adapted from Donat et al. (2017).

thereby forestalling famine, but at the same time industrial agriculture may leak so many nutrients into rivers that dead zones arise in coastal areas at the expense of fisheries.

History is filled with stories of human resourcefulness in response to environmental crises. What worries us most are not over-exploitation or unintended consequences of technology. Those are mistakes humans have made repeatedly and will continue to make, but our responses are often sufficient to correct the problem. Thus, in response to global over-fishing, systems of catch shares have been established all around the world, with great success at restoring fish resources wherever the policy is properly implemented and enforced, and where governments are effective (Costello, Gaines, & Lynham, 2008). What worries us is our ecological ignorance—especially our ignorance regarding positive feedbacks and interactions among stresses that amplify environmental perturbations in ways that surprise us. The numerous positive feedback loops described in Table 2, and the examples of "double whammies" outlined in Section 5 could well be our undoing.

Amplification of perturbations is characteristic of complex nonlinear systems with tight coupling. In 1973, the brilliant theoretical ecologist, Robert May, published a booked entitled, *Stability and Complexity in Model Ecosystems* (May, 1973). May used analyses of systems of nonlinear differential equations to show that complexity (measured by the number of species, and the number of interactions among those species), and strong coupling rendered ecosystems to be highly unstable. Only special configurations of ecosystems could mitigate this inherent instability. Although May's initial models were criticized for being too unrealistic, his predictions about the challenge of maintaining stability in complex systems with many strong interactions have been verified using more realistic models (McCann, Hastings, & Huxel, 1998). Then in 1984, Yale sociologist Charles Perrow published a path breaking book entitled *Normal Accidents* (Perrow, 1984). In this book, Perrow argued that accidents such as the Three Mile Island meltdown should be expected because the nuclear energy system is complex, tightly coupled, and has an inherent catastrophic potential. Finally, in 2017, the MIT finance professor, Andrew Lo, argues that stock market crashes such as the 2008 collapse are to be expected because of the complexity of our financial systems, their tight coupling, and the speed of human responses to perturbations (Lo, 2017). All three of these treatises reveal a deep insight about environmental existential risk. Ecosystems are complex and tightly coupled. Add in humans with globalization, and the pressures on those ecosystems makes for a potentially fragile world.

The good news is that in theory we know how to enhance the resilience of otherwise highly unstable complex systems. Resilience is conferred by: heterogeneity, establishing a modular structure, creating redundancy, introducing negative feedback loops to counteract positive feedback loops, and expecting surprise (Reeves, Levin, & Ueda, 2016). The challenge is turning this theory into practice. For example, one contributing factor to the banking crisis of 2007, was an absence of modularity, in the sense that there were a few big banks and those big banks performed both risky activities (hedge funds) and more traditional banking (Haldane & May, 2011). A regulatory response that embraces resilience theory would limit the size of banks and quarantine the risky hedge fund activities from other areas of banking (Haldane & May, 2011). Applying these principles of designing for resilience more broadly must contend with the fact that several global trends are running in the opposite direction of what one would want for resiliency. For example, increasing global trade and rapid capital flows oppose modularity. The homogenization of cultures by global brands such as Starbucks and McDonald's and the push for uniform regulations reduce heterogeneity. There is evidence that businesses are dying younger as a result of their inability to adapt to increasing complexity; between 1970 and 2010 the average lifespan of companies fell from over 50 years to 31 years (Reeves et al., 2016). Diets worldwide are also being homogenized (Khoury et al., 2014). Only by committing to designing ecological, regulatory, and financial systems for resilience will we be able to substantially reduce the possibility that nature strikes back and leaves us with a post-apocalyptic world of the kind portrayed by Hollywood scriptwriters. Our chances for avoiding the environmental catastrophes will depend on both our actions and on our ability to learn more about the complex natural ecosystems upon which life depends.

We began this paper with an examination of Hollywood's box office disaster hits. This likely seemed frivolous to some readers. But popular culture regarding environmental catastrophes is important because it may lead society to look in the wrong places for existential risks. Movies consistently ascribe disasters to corporate greed and a flawed society. This narrative of either the "villain", or the need for social reform is standard movie fare. No big time Hollywood movie has ascribed an environmental disaster to ignorance about ecosystem dynamics or surprises. It is our thesis that it is our ignorance about the consequences of positive feedbacks and interacting stresses that represent the most basic risk factor when it comes to an environmental apocalypse. If we do not change the cultural narrative, we will think simply policing corporations and better enforcement will avert disaster.

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