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Anthropocene Under Dark Skies: The Compounding Effects of Nuclear Winter and Overstepped Planetary Boundaries

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Abstract: The analysis of global catastrophic events often occurs in isolation, simplifying their study. In reality, risks cascade and interact. Therefore, it is essential to consider the interconnected nature of global risks. This investigation explores the interplay between nuclear winter and planetary boundaries. It may seem reasonable to assume that respecting planetary boundaries, which define a safe operating space for the planet, is preferable before a nuclear war. However, that does not always seem to be the case. For instance, increased nitrogen emissions today could serve as a nutrient buffer during nuclear winter. Contrastingly, mitigating climate change, means an even larger temperature drop in nuclear winter in comparison with pre-industrial times. This exploratory study also highlights planetary boundaries that could enhance human survival if we adhere to their limits, both presently and after a nuclear war. The best example being biosphere integrity, as conserving it has no direct downsides and would make the Earth system more resilient to resist the shock of a nuclear winter.

Keywords: Anthropocene, existential risk, food security, nuclear winter, planetary boundaries

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1. Consequences of a nuclear war

Imagine a future after a full-scale nuclear war. An average person's life would dramatically change overnight. Many major cities could go up blazing in a firestorm, delivering large quantities of soot into the upper atmosphere (Coupe et al., 2019; Tarshish & Romps, 2022) and killing millions (Habbick, 1983). This would change the climate globally (Coupe et al., 2019). While there would be regions like Australia or New Zealand (Boyd & Wilson, 2022) which would still have bearable temperatures, other places like Eastern Europe or Canada would remain frozen for years (Coupe et al., 2019). Under these circumstances, billions of people might starve (Xia et al., 2022).

But it does not have to be this way. Nuclear winter would affect everyone, but the biggest impact would be felt in many of the world's richest countries. The United States and Central Europe would be devastated, both by the direct impact of the nuclear weapons and the indirect effects of the changing climate (Coupe et al., 2019). This gives a strong incentive for those nations to prepare and they have the resources to do so.

Now imagine a different future. A future where humanity is prepared for the worst case. While there are technical solutions, which allow us to scale up resilient food sources like single cell proteins from natural gas (García Martínez et al., 2022) or seaweed (Jehn et al., 2023), many of the problems we would have are linked to the way we are currently overusing the resources of our planet (Steffen et al., 2015). For instance, if we can avoid the overuse of fisheries through regulations now, humanity would be left with more food in a nuclear winter (Scherrer et al., 2020). If we limit our footprint on the planet now, we would have more resources to cope with catastrophes.

It is likely that fisheries are not the only part where being more modest in our resource use today, would allow us extra resources in worst case scenarios. Many of the Earth's systems are under considerable strain (Steffen et al., 2015). Relieving this strain would allow humanity more leeway during catastrophic events. This study explores the interactions between nuclear winter and planetary boundaries to identify which boundaries we should focus on from an existential risks perspective. Nuclear winter can be seen as standing in here for other abrupt sunlight reduction scenarios (ASRSs) such as impact winter or volcanic winter, which refer to sun blocking due to asteroid/comet (bolide) impacts or large volcanic eruptions respectively. While there are differences between those three events, they are likely similar enough to also have comparable interactions with planetary boundaries.

2. Connecting planetary boundaries and nuclear winter

Planetary boundaries are a framework to evaluate the carrying capacity of the Earth System (Rockström et al., 2009; Steffen et al., 2015). They highlight the parts of the earth system which ensure the habitability of Earth and how much strain they are under. This has shown that many important parts of the Earth System may be in a dangerous condition. Only three of the eight currently quantified planetary boundaries are in their safe operating space, which means in the state they had in the Holocene (last 12,0000 years). (Persson et al., 2022; Steffen et al., 2015). Especially, biodiversity and biogeochemical flows are beyond their safe limits (Steffen et al., 2015). This means that they are taxed beyond their capacity and will degrade over time. The more those planetary boundaries are overstepped, the more strain would be put on the Earth's systems that allow humanity to exist. Agriculture in particular would be significantly impacted due to its reliance on boundaries such as freshwater, climate, and phosphorus and nitrogen cycles.

Agriculture would also be massively impacted by nuclear winter (Xia et al., 2022) or other ASRSs. Those are caused by particles in the upper atmosphere blocking out sunlight. This can happen via bolide impact (Tabor et al., 2020), high-magnitude volcanic eruptions (Luterbacher & Pfister, 2015; Rougier et al., 2018), and nuclear war (Coupe et al., 2019; Turco et al., 1983). Given the lower rate of volcanic eruptions and bolide impact, nuclear war is the most likely candidate to lead to such a scenario. However, recent research also shows that volcanic eruptions might be more dangerous and likely than previously thought (Cassidy & Mani, 2022; Mani et al., 2021). Particles in the upper atmosphere would block incoming solar radiation, which would result in considerably lower temperatures and thus lower precipitation. This in turn would significantly decrease food production and make the current global system unviable. Recent research has highlighted that this could lead to global famine (Xia et al., 2022), though this could possibly be counteracted by implementation of resilient foods (Rivers et al., 2022) like sugar from fiber (Throup et al., 2022) single cell proteins from hydrogen (García Martínez et al., 2021), or leaf protein concentrate (Pearce et al., 2019). Still, it is very likely that a nuclear winter would bring a considerable strain on global food production.

Nuclear winter and planetary boundaries work on different time horizons. Overstepping planetary boundaries is a decadal-scale process that gets incrementally worse (Steffen et al., 2015). Nuclear winter on the other hand is sudden and devastating in comparison (Coupe et al., 2019). However, exploring their interaction is still valuable, as their difference in speed does not mean they cannot interact with each other. It merely means that every interaction identified, would get better or worse depending on how much humanity is able to stay clear of overstepping the planetary boundaries.

All this highlights that the main interaction of nuclear winter and planetary boundaries would most likely happen through agriculture. This fits into the classification of global catastrophic risks of Avin et al. (Avin et al., 2018), as this has also highlighted the food system as one of the elements of human society that is most at risk of global catastrophic events. Therefore, we need additional research that looks into possible problems in this area.

3. Other research looking into planetary boundaries and existential risks more broadly

I am not aware of any literature that is specifically looking into the interactions of nuclear winter and planetary boundaries. This is likely due to the fact that the existential risk studies field is relatively small, and has only really started in the last decade (Ord, 2020). Due to its novelty it also is somewhat separated from the traditional science around global problems, like planetary boundaries. In addition, planetary boundaries are still a relatively new concept as well (starting in 2009 (Rockström et al., 2009)). Nuclear winter has been known as a problem since the 1980s (Turco et al., 1983), but did not get much public attention between the end of the Cold War and the invasion of Ukraine. Still, there is some research that is already exploring ideas with a similar spin like this study here:

- Savitch et al. looked into how likely it is that exo-civilizations are creating their own version of an Anthropocene and use simple models to find interactions between civilizations and their planet. Those models might be adaptable to planetary boundaries (Savitch et al., 2021).
- Geoengineering and termination shock in nuclear winter, are hinted at in Tang and Kemp (Tang & Kemp, 2021).
- Kemp et al in their climate endgame paper briefly touch on interactions of climate change and nuclear war (Kemp et al., 2022).

- Thomas Cernev has done research on global catastrophic risk and planetary boundaries in general, but it is more abstract than the direct comparison made here (Cernev, 2022).
- Scherrer et al. have shown that if we make sure to not overuse natural resources (fisheries as the example in their study), the planet would have a bigger buffer to use up during a nuclear winter (Scherrer et al., 2020).
- Baum and Handoh established a framework (Baum & Handoh, 2014) that tried to combine global catastrophic risks and planetary boundaries, but it seems like this has not been built upon in recent years.

4. Interactions

4.1 Biosphere integrity

Biosphere integrity refers to the idea that changes in biodiversity both locally and globally can have significant impacts on the functioning of the Earth system (Steffen et al., 2015). These functions are important to humanity, as they offer ecosystem services like the cleaning of water or the pollination of plants. These services can only be maintained if enough of our environment can remain undisturbed (Mohamed et al., 2022). In the context of planetary boundaries this concept is split into functional and genetic diversity (Steffen et al., 2015). Functional diversity refers to the idea of how much the composition of the biosphere has changed since before the industrial revolution and genetic diversity to the totality of the genetic diversity between all species and individuals. It remains unclear how much biosphere integrity is already damaged by human influence. However, it seems likely that every reduction in functional and genetic diversity is likely to be detrimental to the ability of the biosphere to cope with nuclear winter, as increased biodiversity likely makes ecosystems more resilient to climate extremes (De Boeck et al., 2018). Nuclear winter would have an outsized impact on the global biosphere. The biosphere has survived a number of very large volcanic eruptions (e.g. the Toba eruption (Chesner et al., 1991)), which can also lead to a volcanic winter (Rampino, 2002). However, the mechanisms of volcanic winters and nuclear winters are different. Volcanic winters are mainly caused by sulfates (Luterbacher & Pfister, 2015), while nuclear winters are caused by soot (Coupe et al., 2019). This difference likely makes nuclear winters longer lasting (up to ten years) and therefore introduces a new challenge for the biosphere. The higher the biosphere's integrity, the greater its ability to recover following a long nuclear winter. Mitigating the impact of nuclear winter on humans by reducing starvation could spare some species that would otherwise be eaten by desperate humans or be unaffordable to save in zoos (Denkenberger & Pearce, 2015).

4.2 Climate Change

Climate change and nuclear winter can be seen as two sides of the same coin. Both are climatic changes driven by human actions, one making the planet too hot, the other making it too cold (Pittock, 1988). They are even simulated using the same models, like the Community Earth System Model (CESM) (Coupe et al., 2019; Kay et al., 2015). Current predictions estimate an average warming between 2.1 and 3.9°C by 2100 due to climate change (Liu & Raftery, 2021), while a nuclear winter caused by an all out nuclear war is estimated to cause a peak temperature drop of about 9 °C (Coupe et al., 2019). This means even a largely out of control climate change, would not be enough to counteract the whole cooling effect of a nuclear winter. Still, global warming could dampen some of the effects of a nuclear winter. However, the crops would likely be optimized (either through location or genetic control) to the warmer climate (Minoli et al., 2022), so a sudden temperature reduction would likely still be catastrophic. And this should not be seen as an argument that we should care less about climate change, as it might make us safer against another catastrophic event. The climate system is immensely complex and has many complex feedback loops and tipping points (Armstrong McKay et al., 2022), and we have only limited research on higher temperatures (Jehn et al., 2021, 2022). Also, there simply is no research which looks at how exactly climate change and nuclear winter might interact. Still, we know that nuclear winter would likely influence large climatic patterns like El Niño (Coupe et al., 2021), whose fluctuations are already getting more intense and frequent due to climate change (Cai et al., 2021). Therefore, even though global warming might mitigate the cooling effect of nuclear winter, betting on climate change to solve nuclear winter would be a very risky proposal with unforeseeable consequences. In addition, restoration after a nuclear winter is likely harder if this has to happen in a world under pressure of strong global warming and a world ravaged by climate change has likely a higher probability of nuclear war to start with. Finally, there is a chance that a nuclear winter might push the Earth system in a new equilibria, lasting for hundreds of years. This has happened after large volcanic eruptions in the past (Newhall et al., 2018). As the effects of nuclear winter and volcanic winter are likely somewhat similar (Newhall et al., 2018; Özdoğan et al., 2013), this implies that a longer term shift might also be triggered by a nuclear winter and at least for the ocean system, there are modeling results that show that a longer term shift could happen after a nuclear war (Harrison et al., 2022).

4.3 Novel Entities

The term novel entities refers to the pollution of the environment with man made chemicals, which cause detrimental effects to humans and the environment (Steffen et al., 2015). A well-known example here is the usage of DDT in the 20th century, which almost led to the extinction of several species of birds of prey. As there is no background rate for such emissions, the planetary boundary for novel entities is defined as overstepped if globally more is produced than can be monitored, which is currently the case (Persson et al., 2022). The effects of most of the novel entities are chronic (Persson et al., 2022). This means that they would be detrimental to health during a nuclear winter as well, but not more so than they would have been otherwise. However, nuclear war itself would introduce additional novel entities into the environment, mainly in the form of fallout (Smith & Smith, 1981) and the toxic chemicals produced by fires (Alarie, 2002). In addition, toxic chemicals could be created and distributed through fires and explosions in industrial facilities. Therefore, this would push concentrations further outside of the safe operating space. Still, due to the different nature of emission before and during a nuclear war, it is unclear how much it would help in nuclear winter to stay below this boundary now. Novel entities could be seen as an additional stress factor, not a major disruption in and of itself.

4.4 Stratospheric ozone depletion

The ozone layer protects the Earth’s surface from ultraviolet radiation. It was damaged by the release of ozone depleting substances (for example chlorofluorocarbons). After their ban by the Montreal Protocol the ozone layer started to regenerate and is now mostly intact again (Barnes et al., 2021; Rockström et al., 2009). This leaves ozone depletion as one of the few planetary boundaries which is currently in the safe operating space. However, this would change significantly after a nuclear war. Even the earliest nuclear winter research hypothesized that the ozone layer would be negatively impacted (Turco et al., 1983) and recent research has estimated that the ozone losses would be rapid and global average losses could be as high as 75 % (Bardeen et al., 2021). The same effect, but to a lesser extent, has also been found in simulations for smaller, regional nuclear wars (Mills et al., 2008). The main mechanism is reactions with nitrogen oxides, smoke and the general heating of the upper atmosphere (Bardeen et al., 2021). In the first few years the soot in the atmosphere would shield the surface from most of the incoming ultraviolet radiation.

However, at the same time as soot is cleared from the atmosphere, the ultraviolet radiation rises and could reach UV index values of 35-45 (Bardeen et al., 2021) (not going outside is recommended for UV index > 11). It is estimated to take 12-15 years to return to pre-war UV radiation levels (Bardeen et al., 2021). This means that it is important that we manage to keep the ozone layer intact, to not add to the potentially devastating effect of the nuclear war. However, the effect of nuclear war on the ozone layer could be in a different order of magnitude than problems with the ozone layer so far. This also shows that nuclear war would disrupt one of the few planetary boundaries we are currently managing to keep in safe operating space.

4.5 Atmospheric aerosol loading

This boundary is concerned with the totality of aerosols and their influence on human health and wellbeing. The aerosols also influence solar radiation by scattering it and hydrological cycles by altering cloud formation (Rockström et al., 2009). Both are important for nuclear winter. The main mechanism that could drive nuclear winter is the emission of soot by firestorms (Coupe et al., 2019). Those emissions would contribute significantly to the atmospheric aerosol loading. An all-out nuclear war may emit around 150 Tg of soot in a day to a week (Coupe et al., 2019), while the present-day global soot emissions per year are only around 4-22 Tg (Bond et al., 2004). It is not yet determined whether the planetary boundary for aerosol loading is overstepped now (Steffen et al., 2015). However, there is evidence that the scattering of incoming solar radiation cools the Earth today by a small amount (Bellouin et al., 2020). We also have further evidence for this cooling effect of atmospheric aerosol loading, as the decrease in sulfur content for ship fuel changed the forcing by ship emissions (Yuan et al., 2022). Therefore, removing aerosols now would result in an overall warmer planet, which in turn would not cool as much due to nuclear winter. This raises the same problems as the interaction between climate change and nuclear winter (section 4.2): Is it better to have a warmer planet now, to also have a warmer planet during nuclear winter?

4.6 Ocean acidification

Oceans absorb carbon dioxide as a part of the global carbon cycle. The level of carbon dioxide dissolved in the upper ocean is in equilibrium with the atmosphere and depends strongly on the temperature of the water. As the levels of carbon dioxide rise in the atmosphere, so does the amount of carbon dioxide in the oceans. This in turn decreases the pH in the water. The largest effect of this is the disruption of the life cycles of all organisms who build shells from calcium carbonate. In addition, there is evidence that ocean acidification influences the availability of carbon, nitrogen and phosphorus in the oceans, with unclear effects on the ecosystem (Doney et al., 2009). Since the beginning of the industrial revolution this has led to a drop of around 0.1 in the global average of ocean pH (Intergovernmental Panel on Climate Change, 2014). The most direct impact for humans would be the continuous decrease in the amount of catchable fish in the oceans, as the ecosystems get more and more out of balance and decline in productivity (Cooley & Doney, 2009).

Nuclear winter is predicted to increase the global ocean pH by about 0.05. The effect would mainly be driven by the decrease in sea surface temperature, which shifts the carbonate equilibrium in the water (Lovenduski et al., 2020). While this might seem like a positive effect, modeling results show that it would rather worsen the problem. Marine species would have to adapt to a sharp increase in pH that would only take around a year to shift. However, as the ocean heats up again, as the soot in the atmosphere clears, the pH drops to its previous level, or even lower due to the killed plant matter decomposing. Such a rapid change in ocean chemistry would put a considerable strain on marine ecosystems. In addition, the cooling ocean during nuclear winter can dissolve more carbon dioxide, which in turn decreases the availability of carbonate even further (Lovenduski et al., 2020), which means that the increase in pH does not help shell building organisms.

Overall, the interactions between ocean acidification and nuclear winter would likely be negative. This implies that it is important to slow down ocean acidification now to leave ecosystems more room to adapt during a nuclear winter. This would also increase food availability today and after a nuclear war.

4.7 Biogeochemical flows

Biochemical flows mainly refer to the flows of nitrogen and phosphorus in the environment as two of the main nutrients for plants (Leinfelder et al., 2017). They are summarized under biogeochemical flows, as they are tightly connected. While both nitrogen and phosphorus are needed to sustain any ecosystem, they start to disrupt them as well once their levels change due to anthropogenic emissions (Rockström et al., 2009; Steffen et al., 2015). The main negative effects for both phosphorus and nitrogen are dead zones and shifts in species composition. Dead zones refer to parts of the ocean or other water bodies which have been depleted of oxygen, after eutrophication shifted their species composition and abundance (e.g. algae blooms) (Schindler & Vallentyne, 2008). The main emission pathway for both nutrients are fertilizers, which have been overapplied for decades, especially in major food production countries like Germany (Steffen et al., 2015).

There is no direct way that nuclear war would change biogeochemical flows. Still, there are possible interactions that have to be taken into account. Nuclear winter disrupts agriculture as it is practiced today by shifting climate zones globally and thus making agriculture very difficult if no adaptations are made (Xia et al., 2022). There are possibilities that allow us to still produce food, but those are under the assumption that enough nutrients remain available (Rivers et al., 2022). This leads to the counterintuitive conclusion that overstepping the biogeochemical boundary now, might make humanity more resilient to nuclear winter, as more nutrients are available without needing additional fertilizer, which are likely hard to come by after a nuclear war. Around half of currently used fertilizers are synthetic and any stress on energy and supply chains would be felt. This does not mean that the nutrients available in the environment would allow production levels of today, but they would add a buffer, which would give additional time to set up production and trade for fertilizer in a post nuclear war world. Greater fertilizer production now would also mean larger amounts in storage, which would be helpful in a catastrophe (Mörsdorf, 2021).

4.8 Freshwater use

This boundary is concerned with the influence of humans on the global water cycle. It is in the safe operating space when there is still enough water to sustain ecosystem services (Rockström et al., 2009). Currently this seems to be the case and the freshwater use planetary boundary is largely intact. However, future predicted water usage might bring it closer to its capacity (Rockström et al., 2009).

Nuclear winter generally leads to less evapotranspiration and thus less precipitation (Coupe et al., 2019). Therefore, the overall availability of water would decline, which means that full water storages now would give an additional buffer during nuclear winter. It is unclear how water usage would develop during nuclear winter. However, it might decline, as agriculture is one of the main water users and conventional agriculture would not be possible anymore in many places (Xia et al., 2022). However, it could also be helpful for nuclear winter to have used more water now, as this implies a larger water infrastructure, which could be helpful to allow a better water distribution. Overall, freshwater use now has likely not a very large impact on nuclear winter either way, though both positive and negative impacts are possible.

4.9 Land-system change

Land system change is driven mainly by the expansion of agriculture and the conversion of forests and grasslands to agricultural land (Rockström et al., 2009). This threatens biodiversity and affects both the climate system in general and the hydrological cycle in particular. However, in relation to nuclear winter this boundary could be of lower importance. While deforestation leads to fewer biomass available in nuclear winter, the global amount of trees is so large that this likely remains not an issue (Denkenberger & Pearce, 2015). Also, there might be a positive effect of clearing more land now, which would be also available in nuclear winter. The other way around could be more important though. Nuclear winter would need a major shift in the way we produce food, which also includes relocating crops to warmer regions. In addition, the temperature drop in nuclear winter increases the area needed for crop production (Rivers et al., 2022). Also, nuclear war might cause large scale forest fires, which would at least temporarily change the land use of the affected areas. Therefore, land-system change would likely be accelerated in a nuclear winter. Large parts of currently unused land might need to be converted to agriculture, for example for greenhouses (Alvarado et al., 2020). While those changes may be reverted once the climate returns to normal after a nuclear winter, this would still be a significant change in those systems, because they would need a considerable amount of time to be able to return to their pre-war state.

5. Discussion and conclusion

Planetary boundaries are defined to highlight how we should treat the Earth to make it habitable for the long term. The included assumption here is that staying in the safe operating space is always better. This study was a first exploration of how this assumption holds true when the planetary boundaries interact with existential risks. The insights gained here show that this assumption is often true, but not always. Overstepping planetary boundaries can either increase or decrease nuclear winter survivability, depending on which boundary has been broken (Figure 1). In addition, all boundaries are interconnected, and fixing one boundary may have unintended consequences for others.

Overstepping the boundary on climate change results in an increase in temperature, which in itself has negative effects on the Earth system. However, this increase in temperature also means that during a nuclear winter, the planet would be cooled down from an elevated level, ultimately resulting in a lower peak cooling. This interaction might seem positive, but it remains unclear if it could lead to unforeseen consequences. Therefore, it is highly uncertain if this effect of climate change could be positive.

Overstepping the boundary on biogeochemical flows however might provide humanity with a nutrient buffer if overstepped, but it also has clear downsides today, like dead zones in the oceans. Therefore, it is essential to balance the present needs of human society with the long-term risks and benefits associated with overstepping planetary boundaries.

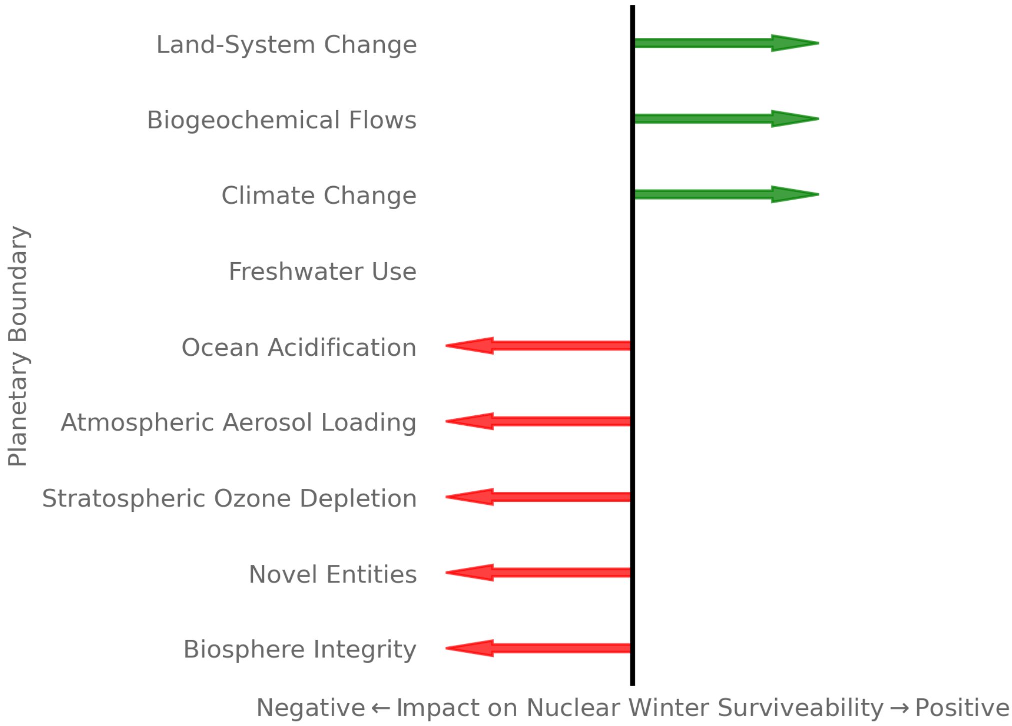

Figure 1: Visual summary and qualitative assessment of the impact of overstepping planetary boundaries on the chances of survival for humanity after a nuclear war.

On the other hand, certain planetary boundaries, if overstepped, likely have only a negative impact on nuclear winter survivability. Ocean acidification, for example, would be sensitive to the effects of a nuclear war and is already under stress, which diminishes global food production today and has been highlighted as a strong risk (Kareiva & Carranza, 2018). Therefore, stopping ocean acidification has clear upsides. However, it is also the case that planetary boundaries are interconnected, and ocean acidification is mainly caused by elevated carbon dioxide levels. Bringing those back to preindustrial levels would stop ocean acidification, but also remove the temperature buffer provided by climate change. All of those risks are connected and better results can be expected when their interactions and feedback loops are considered (Ward et al., 2022).

Changing the state of the earth relative to planetary boundaries would be an enormous undertaking. Therefore, directed existential risk reduction activities are likely more cost-effective. However, if mitigating global catastrophes could be used to nudge existing funding in this space towards work on planetary boundaries that would be most synergistic with global catastrophes, this may be promising.

These findings highlight the importance of identifying and staying withing boundaries that may provide upsides before and after a nuclear war. Stratospheric ozone depletion and biosphere integrity appear promising in this regard, as they could have a clear negative effect. But even here there are likely differences when it comes to costs and benefits. For example, the effect of nuclear winter on the ozone layer would be quite strong and likely dwarfs any reconstruction of the ozone layer now and biodiversity has more of a supporting role and its impact on human life are more indirect (Kareiva & Carranza, 2018). It is difficult to assess which planetary boundary should be given priority from a nuclear winter perspective. This problem gets even more difficult when we consider how boundaries might interact. For example, recent research has highlighted that rising fertilizer prizes and thus lower fertilizer could increase the land area used for agriculture considerably (Alexander et al., 2023).

Given the tentative evidence presented here biosphere integrity could possibly be the planetary boundary with the highest net positive effect on nuclear winter survivability, albeit a diffuse one. Preserving biosphere integrity now is clearly positive, it does not have obvious, strong interactions with other boundaries and it would provide humanity with a more stable Earth system overall, both now and in the nuclear winter. Still, this paper here is just a first step in this direction and more research is needed, especially when it comes to interactions and feedback loops between the planetary boundaries themselves and nuclear winter.

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