# Ozone depletion, ultraviolet radiation, climate change and prospects for a sustainable future

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# Contributions of the Montreal Protocol to a sustainable Earth

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## ***1. Stratospheric ozone depletion, the Montreal Protocol, and the Environmental Effects Assessment Panel***

Thirty-three years ago, an unprecedented thinning of stratospheric ozone was reported over Antarctica[1]. In response to concerns about elevated exposure to solar ultraviolet-B radiation (UV-B; wavelengths 280-315 nm) resulting from ozone depletion, the international community mobilized and worked together to understand the causes and find a solution to this dramatic change in Earth's environment. The policy solution that emerged to address this global environmental problem was the 1985 Vienna Convention for the Protection of the Ozone Layer. In this international agreement the United Nations recognized the fundamental importance of preventing the damaging effects of stratospheric ozone depletion, whether on human health or the environment. This convention was followed by the 1987 *Montreal Protocol on Substances that Deplete the Ozone Layer* with its subsequent amendments, adjustments, and decisions that were negotiated to control the consumption and production of anthropogenic ozone-depleting substances, including chlorofluorocarbons (CFCs). The Montreal Protocol now has the unique distinction of being the only treaty, ever, of any type, ratified by all 197 countries of the United Nations. The Parties to the Montreal Protocol base their decisions on scientific, environmental, technical, and economic information provided by three assessment Panels (Box 1). All three panels provide full assessment reports to the Parties every four years (quadrennial reports) and shorter, periodic updates in the intervening years as needed.

The implementation of the Montreal Protocol has successfully prevented the uncontrolled global depletion of the stratospheric ozone layer[2,3]. Concentrations of ozone-depleting substances have been declining in the stratosphere since the late 1990s. While significant seasonal ozone depletion over Antarctica has occurred annually since the 1980s (called the "ozone hole"), there have been small, but significant, positive trends in total column ozone in Antarctica in spring over the period 2001-2013. Global mean total ozone has been projected to recover to pre-1980 levels by about the middle of the 21st century, assuming full compliance to the Montreal Protocol[2].

Many of the chemical compounds controlled by the Montreal Protocol are not only involved in depletion of stratospheric ozone, but are also potent greenhouse gases[4]. Modeling studies indicate that, in the absence of the Montreal Protocol, global mean temperatures would have risen by more than 2°C by 2070, due to the warming effects from ozone-depleting substances alone[5]. The adoption of the Kigali Amendment to the Montreal Protocol in 2016 limits the production and consumption of hydrofluorocarbons (HFCs), powerful greenhouse gases that are used as substitutes to ozone-depleting substances[6]. This amendment has further broadened and strengthened the scope of the Montreal Protocol, creating an effective international treaty that not only addresses stratospheric ozone depletion, but is doing more to mitigate global climate change than any other human actions to date[7-10].

One of the important reasons for the success of the Montreal Protocol has been its foundation on high quality science, which not only improves our understanding of the causes and mechanisms of ozone depletion, but also of the environmental effects of these atmospheric changes. The Environmental Effects Assessment Panel (EEAP) is specifically charged with providing regular assessments of the state of the science on the environmental effects of ozone depletion and consequent changes in UV radiation at Earth's surface, and the interactive effects of climate change (Box 1 and Fig. 1).

**BOX 1. The Environmental Effects Assessment Panel**

The Environmental Effects Assessment Panel is one of the three assessment panels established by the Montreal Protocol to assess various aspects of stratospheric ozone depletion. These three Panels have complementary charges. The Scientific Assessment Panel assesses the status of the depletion of the ozone layer and relevant atmospheric science issues. The Technology and Economic Assessment Panel provides technical and economic information to the Parties on alternative technologies to replace ozone depleting substances. The Environmental Effects Assessment Panel (EEAP) assesses the full range of potential effects of stratospheric ozone depletion, UV radiation and the interactive effects of climate change on human health, aquatic and terrestrial ecosystems, biogeochemical (e.g., carbon and other elements) cycles, air quality, and materials for construction and other uses. Forty-nine scientists from nineteen countries contributed to the 2018 EEAP Quadrennial Assessment.

Here, we summarize key findings from the most recent EEAP Quadrennial Assessment, and consider the significant policy and societal implications of these environmental effects. We specifically highlight the multiple ways by which the Montreal Protocol is contributing to environmental sustainability and human health and well-being consistent with many of the United Nations Sustainability Goals (Box 2). More in-depth information on ozone depletion and its environmental effects can be found in the full Assessments published by the Ozone Secretariat of the United Nations Environment Programme (https://ozone.unep.org) and elsewhere (*Photochemical & Photobiological Sciences* journal)[11-17]. By focusing on the interactions between stratospheric ozone dynamics, UV radiation, and climate change, the report from the EEAP complements that of the UN's Intergovernmental Panel on Climate Change (IPCC;https://www.ipcc.ch; summarized by Pachauri, et al.[18]) to provide a comprehensive assessment on the environmental effects of global changes in Earth's atmosphere.

**BOX 2. The United Nations Sustainability Goals addressed by the Environmental Effects Assessment Panel 2018 quadrennial report.**

Our findings address 10 of the 17 UN Sustainability Goals: 2. Zero hunger, 3. Good health and well-being, 6. Clean water and sanitation, 7. Affordable and clean energy, 9. Industry, innovation and infrastructure, 11. Sustainable cities and communities, 12. Responsible consumption and production, 13. Climate action, 14. Life below water, 15. Life on land. More information on these sustainability goals can be found at https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

## *2. Key findings and highlights*

### *2.1 Stratospheric ozone, climate change and UV radiation at Earth's surface*

The effects of stratospheric ozone depletion and climate change interact via several direct and indirect pathways that can have consequences for human well-being, food and water security, and ecosystem sustainability (Fig. 1). Climate change can modify stratospheric ozone depletion by perturbing temperature, moisture, and wind speed and direction in the stratosphere and troposphere[19]. Conversely, it is now clear that ozone depletion in the southern hemisphere is directly contributing to climate change by altering regional atmospheric circulation patterns in this part of the globe[20] which, in turn, affect weather conditions, sea surface temperatures, ocean currents, and the frequency of wildfires[21-25]. These ozone-driven changes in climate are currently exerting significant impacts on the terrestrial and aquatic ecosystems in the southern hemisphere ([13,17,26,27]; Box 3). In the northern hemisphere, similar, but smaller effects of ozone depletion on climate may exist[11], but there are no reports as yet linking these changes to environmental effects.

Depletion of stratospheric ozone leads to increased UV-B radiation at Earth's surface[11]; the resultant changes in UV-B radiation can directly affect the environment, including the organisms that live there. Because of the success of the Montreal Protocol, present-day increases in UV-B radiation due to stratospheric ozone depletion have been negligible in the tropics, small (5-10%) at mid-latitudes, and large only in polar regions. As stratospheric ozone recovers over the next several decades, the clear-sky noon-time UV Index is expected to decrease (e.g., by 2-8% at mid-latitudes depending on season and precise location, and by 35% during the Antarctic October ozone hole[11,28]).

Independent of stratospheric ozone dynamics, climate change is increasingly contributing to changes in surface UV-B radiation[11,29]. Unlike ozone depletion, these climate change-driven effects influence the amount of surface solar radiation not just in the UV-B but also in the ultraviolet-A (UV-A; 315-400 nm) and visible (400-700 nm) parts of the solar spectrum. These changes are important as many of the environmental and health effects caused by UV-B are also influenced, to varying degrees, by UV-A and visible radiation[12,13,17].

Future changes in surface solar UV radiation (UV-B and UV-A) will depend heavily on changes in aerosols, clouds, and surface reflectivity (e.g., snow and ice cover). Climate change is altering cloud cover with some regions becoming cloudier and others less cloudy[30]. Increased cloud cover generally tends to reduce UV radiation at Earth's surface, but effects vary with type of clouds[31] and their position relative to that of the sun[32]. Aerosols (solid and liquid particles suspended in the atmosphere[15]) reduce and scatter UV radiation, and the type and amounts of aerosols in the atmosphere are affected by volcanic activity, the emissions of air pollutants, the frequency and extent of wildfires and dust storms, and other factors, many of which are affected by climate change[11,14,33]. In heavily polluted areas (e.g., southern and eastern Asia), improvements in air quality are expected to increase levels of UV radiation to pre-industrial levels (i.e., before extensive aerosol pollution), with the extent of changes contingent on the degree to which emissions of air pollutants are curtailed. High surface reflectance from snow or ice cover can enhance incident UV radiation because some of the reflected UV radiation is scattered back to the surface by aerosols and clouds in the atmosphere. Consequently, climate change-driven reductions in ice or snow cover, which is occurring in polar regions and mountains, will likely decrease surface UV radiation in these regions[11]. At the same time, this would increase the UV exposure of soils and waters that would previously have been below the snow or ice.

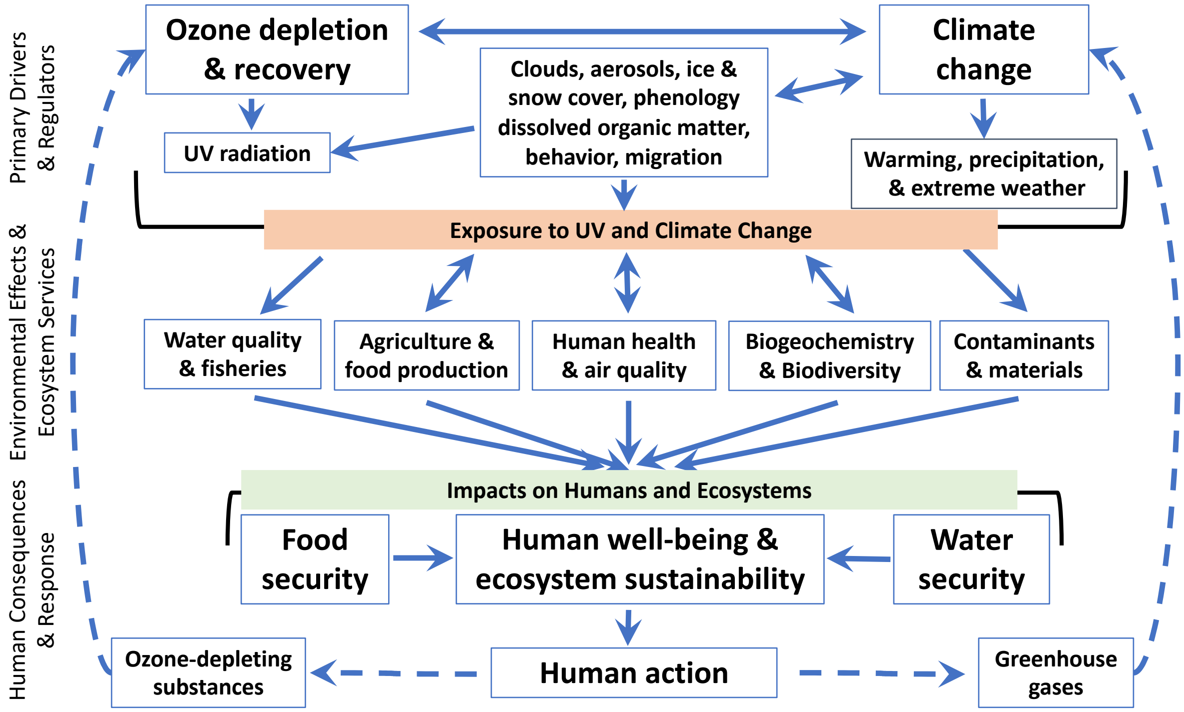


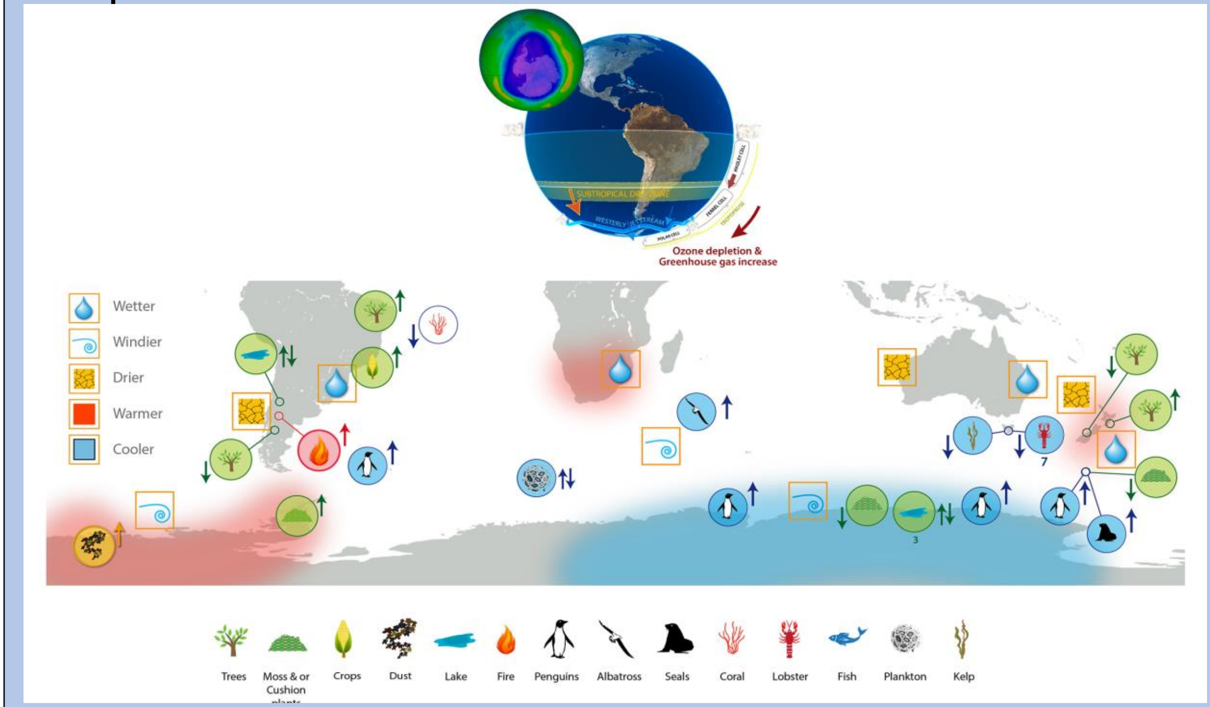
**Figure 1.** Linkages between stratospheric ozone depletion, UV radiation, and climate change, including environmental effects and potential consequences for human well-being, food and water security, and the sustainability of ecosystems (solid lines), with important feed-back effects driven by human action (dashed lines) and other processes (double-arrow solid lines).

### *2.2 UV exposure and climate change*

The effects of UV radiation on organisms, including humans, and materials, depends on levels of UV exposure. This is determined by a number of factors, including many that are influenced by climate change. Importantly, these climate change-driven effects can result in either increases or decreases in exposures to solar UV radiation, depending on location, time of year, individual species, and other circumstances. Some of the most important regulators of UV exposure include:

- Behavior: The exposure of humans to UV radiation varies from one-tenth to ten times the average for the population[34], depending on the time people spend indoors vs. outdoors and under shade structures. The exposure of the skin or eyes to UV radiation further depends on the use of sun protection such as clothing or sunglasses; the UV dose to biological structures in the skin is mediated by skin pigmentation and use of sunscreen[12]. Warmer temperatures and changing precipitation patterns resulting from climate change will alter human patterns of sun exposure[35], but the direction and magnitude of this effect is likely to be highly variable globally. Many animals, such as insects and birds, can sense UV radiation and some use behavior to avoid exposure to prolonged periods of high UV radiation[36,37].
- In response to climate change, many plants and animals are migrating to higher latitudes and elevations[38,39], or deeper into lakes and oceans[40]. Because of the natural gradients in solar UV radiation that exist with latitude, altitude and water depth[11,17], these shifts in distributions will expose organisms to UV radiation conditions that are different from those to which they may be normally accustomed.
- Climate change is altering phenology, including plant flowering, spring bud-burst in trees, and animal emergence and breeding[38,41,42] and these changes in the timing of critical life cycle events will alter UV exposures as UV radiation varies naturally with season.
- Modifications in vegetation cover (e.g., drought, fire, and pest-induced die-back of forest canopies or shrub invasion in grasslands) driven by changes in climate and land-use alter the amount of sunlight reaching many ground-dwelling terrestrial organisms (e.g.,[43]).
- Reductions in snow and ice cover and the timing of melt driven by climate change is influencing surface UV reflectance and the penetration of UV into rivers, lakes, oceans, and wetlands[44]. Additionally, increases in extreme weather events (e.g., high rainfall and floods) increase the input of dissolved organic matter and sediments into coastal and inland waters that can reduce water clarity and the UV exposure of aquatic organisms[17,45].

**BOX 3. Environmental effects of ozone-driven climate change in the southern hemisphere.**



Stratospheric ozone depletion and increases in greenhouse gases have both had measurable impacts on southern hemisphere climate, moving the winds and associated latitudinal bands of high and low rainfall further south[20] (inset globe). As a result, aquatic and terrestrial ecosystems, including agriculture, have been impacted in a number of ways[13,17]. For instance, the productivity of the Southern Ocean is changing, decreasing over much of the ocean, but increasing in other areas with corresponding effects on carbon dioxide uptake from the atmosphere. More productive areas already support increased growth, survival and reproduction of sea birds and mammals including albatross, several species of penguins and elephant seals. Regional increases in oceanic productivity are likely to support increased fisheries. In contrast, warmer sea surface temperatures related to these climate shifts are correlated with declines in both kelp beds in Tasmania and corals in Brazil[17]. On land, changing rainfall patterns have resulted in increased agricultural productivity in some regions and drought conditions in others. Drier conditions have resulted in increasing salinity in lakes and changed lake fauna in East Antarctica and the eastern Andes[13,47]. On the Antarctic Peninsula, terrestrial ecosystem productivity has increased with warmer and wetter conditions, while in East Antarctica ecosystems are responding negatively to cooling and drying[27]. These climatic changes have implications for food and water security as well as for human well-being through increased wild fire frequency and air pollution. While our understanding of the extent of these impacts has improved considerably in the last four years, there are likely many other impacts that have not yet been quantified. Actions under the Montreal Protocol have moderated these climatic and subsequent ecosystem changes, by limiting ozone depletion as well as reducing greenhouse gases. Without the Montreal Protocol, similar climatic changes would likely have become manifest across the globe and would have been more extreme in the southern hemisphere. Images adapted from Robinson and Erickson[26].

## *2.3. Environmental effects of changing exposure to UV radiation*

Changes in exposure and sensitivity to solar UV radiation, driven by ongoing changes in stratospheric ozone and climate, have the potential to affect materials, humans, and many other organisms in ways that have consequences for the health and well-being of people and ecosystem sustainability. Below we highlight some of these effects from the recent Quadrennial Assessment of the EEAP.

*2.3.1. Impacts on human health and air quality*

Higher exposure to UV radiation increases the incidence of skin cancers and other UV-induced human diseases, such as cataracts and photosensitivity disorders[12]. Increases in the incidence of skin cancer over the last century appear largely attributable to changes in behavior that increase exposure to UV radiation; these changes highlight how susceptible human populations would have been to uncontrolled stratospheric ozone depletion. Skin cancer is the most common and most expensive cancer in many developed countries with predominantly light-skinned populations[12]. Exposure to UV radiation accounts for 60-96% of the risk of developing cutaneous malignant melanoma in light-skinned populations: ca.168,000 new melanomas in 2012 were attributable to 'excess' exposure to UV radiation (above that of a historical population with minimal exposure)[46]. Modelling studies show that implementation of the Montreal Protocol has avoided devastating effects on human health including large increases in skin cancer incidence in light-skinned populations and high ambient UV levels (e.g., UV Index > 50 in the tropics[47]) that would require minimizing time outdoors to preserve health ([48]; Box 4).

Exposure to UV radiation contributes to the development of cataract, the leading cause of impaired vision worldwide (12.6 million blind and 52.6 million visually impaired due to cataract in 2015)[49]. Particularly in low income countries – often with high ambient UV radiation – access to cataract surgery may be limited, making this a major health concern. The role of exposure to UV radiation for another major cause of visual impairment globally particularly in older people, age-related macular degeneration, remains unclear[12].

Concern about high levels of UV-B radiation as a consequence of stratospheric ozone depletion was an important driver for the development of programs for sun protection in many countries. These programs focus on promoting changes in people's behavior, supported by structural and policy-level interventions[50]. Sun protection programs have been shown to be highly cost-effective in preventing skin cancers[51]. Behavioral strategies need to be informed by the real-time level of ambient UV radiation (provided by the UV Index) and include controlling time outdoors together with using clothing, hats, sunscreen and sunglasses to reduce exposure to UV radiation. Behavioral changes can be facilitated by providing shade in public spaces such as parks, swimming pools, and schools, and improving access to sunscreen[50].

Changes in UV radiation and climate can further impact human health by influencing air quality[15]. A number of recent international assessments have concluded that poor air quality is a significant global health issue and is estimated to be the largest cause of deaths globally due to environmental factors[15]. UV radiation causes the production of ground-level ozone and some types of particulate pollutants. Future recovery of stratospheric ozone and climate may change ground-level ozone via decreases in UV radiation and increases in downward transport of stratospheric ozone[15]. Modelling studies for the USA indicate that reductions in UV radiation due to stratospheric ozone recovery will lead to decreased ground-level ozone in some urban areas but slight increases elsewhere[52]. Because large populations are already affected by poor air quality, even small relative changes in UV radiation can have significant consequences for public health.

Exposure to UV radiation also has benefits for human health; it is the major source of vitamin D for much of the world's population. Vitamin D is critical to healthy bones, particularly during infancy and childhood. There is also growing evidence of a range of other benefits of exposure to UV radiation through both vitamin D and non-vitamin D pathways, for example, for systemic autoimmune diseases and non-cancer mortality, and in the prevention of myopia[12]. Gaps in our knowledge prevent calculations of the amount of UV radiation necessary to balance the risks with benefits, particularly as this likely varies according to age, sex, skin type, and location.

Projected changes in climate will alter the balance of risks vs. benefits for human populations living in different regions. For example, lower ambient UV-B radiation at high latitudes will increase the risk of vitamin D deficiency where this risk is already substantial. Conversely, warmer temperatures may encourage people in cooler regions to spend more time outdoors, increasing exposure to not just UV-B, but all wavelengths of solar radiation. Changes in snow and ice cover will alter the amount of reflected UV radiation and thus exposure of the eyes to UV radiation, possibly increasing the risk of eye diseases.

### *2.3.2 Impacts on agriculture and food production*

There is little evidence to suggest that modest increases in solar UV radiation have any substantial negative effect on crop yield and plant productivity[13]. How food production would have been impacted by the large increases in solar UV radiation in the absence of the Montreal Protocol is unclear. One analysis, based on data from a number of field studies conducted in regions where ozone depletion is most pronounced (i.e., high latitudes), concluded that a 20% increase in UV radiation equivalent to a 10% reduction in stratospheric ozone has only reduced plant production by about 6% (i.e., a 1% reduction in growth for every 3% increase in UV)[53]. To what extent this relationship would hold for UV levels >2-fold higher than present (i.e., the 'World Avoided' scenario; Box 4[47]) is uncertain and represents an important knowledge gap.

It is likely that by mitigating climate change, the Montreal Protocol has reduced the vulnerability of agricultural crops to rising temperatures, drought, and extreme weather events. However, at a regional scale, changes in southern hemisphere rainfall, driven by ozone depletion and climate change, have been linked to both increases and decreases in agricultural productivity (Box 3) and these effects may reverse as the ozone hole recovers. Climate change factors including drought, high temperatures, and rising carbon dioxide levels can also modify how UV radiation affects crop plants, but effects are complex and often contingent on growth conditions. In some cases these climate change factors can increase sensitivity to UV radiation (e.g., elevated carbon dioxide can weaken UV defenses in maize[54]). In other cases exposure to UV radiation can increase plant tolerance to drought[55]. Increases in ground-level ozone resulting from reduced UV radiation resulting from the recovery of stratospheric ozone could negatively affect crop yields[15]. Understanding these, and other UV-climate change interactions can inform growers and breeders as to relevant agricultural practices that could aid in maintaining crop yields in the face of evolving environmental change.

UV radiation can also have beneficial effects on plants and these effects are often mediated by specific photoreceptors that act to regulate plant growth and development[56]. These non-damaging effects include alterations in plant chemistry that then lead to changes in the nutritional quality of food[57] and the ability of plants to defend themselves against pests and pathogens[58]. Consequently, decreases in exposure to UV radiation as affected by changes in stratospheric ozone and climate, or changing agricultural practices (e.g., planting dates or sowing densities), could reduce plant defenses and thereby affect food security in ways other than just the direct effects on yield[59]. For certain vegetable crops, low levels of UV radiation are increasingly being used to manipulate plant hardiness, food quality and pest resistance[60].

### *2.3.3 Impacts on water quality and fisheries*

Climate change is altering the mixing patterns in the water column of lakes and oceans, with deeper mixed layers in some regions and shallower mixed layers in others. These changes are altering the UV exposure and fundamental structure of aquatic ecosystems and consequently their ecosystem services (e.g. water quality, fisheries productivity) in regionally specific ways[17]. The sensitivity to damage induced by UV radiation for the often very clear-bodied larvae of many commercially important fish species, combined with the distribution of these larvae in high UV surface waters, have the potential to reduce the year class strength and subsequent harvest potential for fisheries[61]. In contrast, reductions in the UV transparency of clear-water lakes may increase the potential for invasions of UV-sensitive warm-water species that can negatively affect native species[62].

Climate-change related increases in heavy precipitation and melting of glaciers and permafrost are increasing the concentration and color of UV-absorbing dissolved organic matter and particulates[14,17]. This is leading to the “browning” of many inland and coastal waters, with consequent loss of the valuable ecosystem service in which solar UV radiation disinfects surface waters of parasites and pathogens[45]. Region-specific increases in the frequency and duration of droughts have the opposite effect, increasing water clarity and enhancing solar disinfection, as well as altering the depth distribution of plankton that provide critical food resources for fish[33,40].

### *2.3.4 Impacts on biogeochemical cycles, climate system feedbacks, and biodiversity*

Exposure to solar UV and visible radiation can accelerate the decomposition of natural organic matter (e.g., terrestrial plant litter, aquatic detritus, and dissolved organic matter) through the process of photodegradation, resulting in the emission of greenhouse gases including carbon dioxide and nitrous oxide[63,64]. Climate change-driven increases in droughts, wildfires, and thawing of permafrost soils have the potential to increase photodegradation (e.g., [14,65]), thereby fueling a positive feedback on global warming; however, the scale of this effect remains an important knowledge gap.

Species of aquatic and terrestrial organisms differ in their tolerances to UV radiation and these differences can lead to alterations in the composition and diversity of ecological communities under elevated UV conditions[13,17]. UV radiation also influences herbivory and predator-prey interactions which then alters trophic interactions, energy transfer, and the food webs in ecosystems[66]. Presently, ozone-driven changes in regional climate in the Southern Hemisphere are threatening the habitat and survival of a number of species, including plants growing in the unique high-elevation woodlands of the South American Altiplano[67] and moss and other plant communities in Antarctica[27], but enhancing reproductive success of some marine birds and mammals[13,17](Box 3). To what extent the Montreal Protocol has specifically contributed to the maintenance of biodiversity in ecosystems is unknown, but losses in species diversity in aquatic ecosystems are known to be linked to high UV radiation exposure which can then lead to a decline in the health and stability of these systems[33].

### *2.3.5 Impacts on contaminants and materials*

Solar UV radiation plays a critical role in altering the toxicity of contaminants[14,17]. Exposure to UV radiation increases the toxicity of contaminants such as pesticides and polycyclic aromatic hydrocarbons (PAHs) to aquatic organisms such as fish and amphibians. In contrast, UV-B radiation transforms the most toxic form of methyl mercury to forms that are less toxic, reducing the accumulation of mercury in fish[68]. Although the degradation of many pollutants and water-borne pathogens by solar UV radiation is affected by changes in stratospheric ozone, other factors such as dissolved organic matter are more important in regulating underwater UV radiation and hence photodegradation of these pollutants[14]. Advances in modeling approaches are allowing improved quantification of the effects of global changes on the fate of aquatic pollutants.

Sunscreens are in widespread use, including in cosmetics, as part of the suite of approaches to sun protection for humans. It is now recognized that sunscreens wash into coastal waters, with potential effects on aquatic ecosystems. The toxicity of artificial sunscreens to corals[69], sea urchins[70], fish[71], and other aquatic organisms, has led the state of Hawaii, USA, to pass legislation banning the use of some sunscreens. Similar legislation is under consideration by the European Union[72].

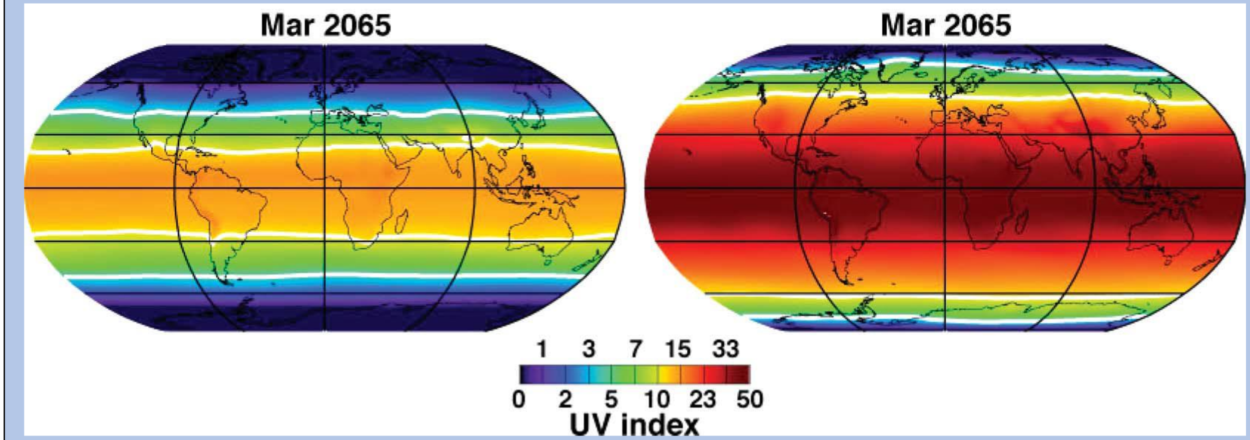
Microplastics (plastic particles < 5mm) are now ubiquitous in the world's oceans and pose an emerging serious threat to marine ecosystems with many organisms now known to ingest them[73]. Microplastics are formed by the UV-induced degradation and breakdown of plastic products and rubbish exposed to sunlight. Microplastic pollutants occur in up to 20% or more of fish marketed globally for human consumption[74]. Although the toxicity of microplastics is unknown, higher temperatures and UV levels accelerate the fragmentation of plastics, potentially threatening food security.

Until very recently, plastics used in packaging and building were selected and optimized on the basis of durability and performance[16]. However, the present focus on increased sustainability, for example the trend towards 'green buildings', now requires such choices to be environmentally acceptable as well. This includes the increased use of wood, which is renewable, carbon-neutral, and low in embodied energy, in place of plastics, where appropriate. Some of these materials are vulnerable to accelerated aging when exposed to UV radiation. Current efforts are moving forward to identify and develop novel, safer, effective, and 'greener' additives (colorants, plasticizers, stabilizers) for plastic materials and wood coatings. Harsher weathering climates, as predicted due to climate change, would require even more effort along this direction.

## BOX 4. Environmental effects in the ‘World Avoided’

This assessment focusses largely on the environmental effects of changes in stratospheric ozone that have occurred, and are predicted to occur, with effective implementation of the Montreal Protocol and its amendments. At present, lack of relevant research has prevented us from considering the health and environmental impacts that would have resulted if the ozone layer had not been protected by the Montreal protocol. Yet it is worth noting that current understanding of this ‘World Avoided’, provides context for the effects observed with the successful implementation of the Montreal Protocol.

There are a number of published models of changes in the ozone layer without the Montreal protocol- in the ‘World Avoided’[3]. All point to progressive loss of ozone that would have accelerated over time and extended to affect the entire planet by the second half of this century. This collapse in global ozone would have resulted in UV Index values above the current extreme of 25 becoming common-place over almost all inhabited areas of the planet, and as high as 50 in the tropics, more than four times the UV index that is currently considered ‘extreme’ by the World Health Organization.



Combining these models of ozone and UV radiation with understanding of the links between exposure to excessive UV radiation and the risk of skin cancers has allowed some quantitative estimates of the incidence of skin cancer in the ‘World Avoided’. Different studies have considered different time-scales and/or different geographical regions, but all conclude that the successful implementation of the Montreal Protocol will prevent many millions of cases of skin cancers. For example, a report by the United States Environmental Protection Agency[48], showed that when compared with a situation of no policy controls, full implementation of the Montreal Protocol and its Amendments is expected to avoid more than 250 million cases of skin cancer in the USA alone. The same report estimates that the Montreal Protocol will have prevented more than 45 million cases of cataracts in the USA. Substantial gaps in our knowledge currently limit our ability to quantitatively assess the full range of human and environmental benefits of the successful implementation of the Montreal Protocol.

There are multiple anthropogenic sources that will release trifluoroacetic acid (TFA) into the environment, including some relevant to the Montreal Protocol. Specifically, some compounds being used as substitutes for CFCs, including hydrochlorofluorocarbons (HCFCs) and HFCs, are known to degrade to TFA in the atmosphere. These sources will contribute to a slight increase in TFA concentrations in surface water, but this is not expected to pose a risk to humans or the environment[75].

## 3. Conclusions and Knowledge Gaps

The Montreal Protocol has been successful in preventing the global depletion of stratospheric ozone and consequently large-scale increases in solar UV-B radiation. Full recovery of the ozone layer is expected by the middle of this century and levels of UV-B radiation at Earth's surface are beginning to decrease. Thus, because of the Montreal Protocol, we have averted a "worst-case" scenario of stratospheric ozone destruction, prevented the resultant high levels of UV-B radiation at Earth's surface, and so avoided major environmental and health impacts (Box 4).

We are confident in our qualitative predictions of the environmental effects that have been avoided because the Montreal Protocol has successfully controlled stratospheric ozone depletion. However, quantification of many of the environmental benefits resulting from the success of the Montreal Protocol remains a major challenge. The same knowledge gaps that constrain modelling of most environmental effects in the 'World Avoided' scenario also constrain quantification of the potential impacts of any current or future threats to the ozone layer. Recent reports of unexpected increases in emissions of CFC-11[76] are currently expected to have only small effects on ozone depletion[2], and so on health or environmental responses. However, were such unexpected emissions to persist and increase in the future, or new threats emerge, environmental and health impacts could be substantially magnified. New threats might include "geoengineering" activities proposed to combat the warming caused by greenhouse gases, which could have consequences for UV radiation. In particular, proposals to inject sulfuric aerosols into the stratosphere to reduce solar radiation at Earth's surface[77] would likely reduce stratospheric ozone in most latitudes, which would then lead to increases in surface UV-B radiation[11,78,79].

Meeting the challenge of improved quantification of the environmental effects of future changes in stratospheric ozone requires addressing several significant gaps in current knowledge. First, we need a better understanding of the fundamental responses of a diversity of organisms to UV radiation, particularly how species respond to the different wavelengths of UV radiation (i.e., their action spectra). Second, we need to better understand the full scope of not only the adverse (e.g., photosensitivity drug reactions), but the beneficial effects of UV radiation on humans and other species. Third, we need long-term, large-scale field studies to better understand how changes in UV radiation, together with other climate change factors, including extreme events, influence intact ecosystems[80]. Taken together, all three would increase our ability to develop models that could be used to quantify effects of UV radiation on living organisms and materials on scales ranging from individuals to ecosystems and the planet.

As a result of shifting geographic ranges (including migration of humans and other species that is induced by climate change) and seasonal timing of life-cycle events due to climate change, it is apparent that many organisms, including human populations, will be confronted with novel and interactive combinations of UV radiation and other environmental factors. These environmental changes will occur together with alterations in the structure and composition of ecological communities[81], which will then indirectly affect the growth, reproduction, and survival of multiple species. How humans and ecosystems respond to changes in UV radiation against this backdrop of simultaneous, multi-factor environmental change remains a major knowledge gap. Quantifying these effects is extremely challenging, where many of the outcomes are contingent on human behavior and societal responses that are difficult to predict (Fig. 1).

The focus of concern regarding elevated exposure to UV radiation has historically been on human health. Yet terrestrial and aquatic ecosystems provide essential services on which human health and well-being ultimately depend. In addition to being critical for human health and well-being, environmental sustainability and the maintenance of biodiversity are also important at a higher level if we are to maintain a healthy planet[82]. The topics covered by the Environmental Affects Assessment Panel report embrace the full complexity and inter-relatedness of our living planet, and the Montreal Protocol demonstrates that globally united and successful action on complex environmental issues is possible.

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