



UNIVERSITY
OF WOLLONGONG
AUSTRALIA

University of Wollongong
Research Online

Faculty of Science, Medicine and Health - Papers:
Part B

Faculty of Science, Medicine and Health

2019

Linkages between stratospheric ozone, UV radiation and climate change and their implications for terrestrial ecosystems

Janet F. Bornman

United Nations Environment Programme, Environmental Effects Assessment Panel, Murdoch Universit

Paul W. Barnes

Loyola University New Orleans, pwbarnes@loyno.edu

T Matthew Robson

University of Helsinki

Sharon A. Robinson

University of Wollongong, sharonr@uow.edu.au

Marcel A.K Jansen

University College Cork

See next page for additional authors

Publication Details

Bornman, J. F., Barnes, P. W., Robson, T. Matthew, Robinson, S. A., Jansen, M. A.K., Ballare, C. L. & Flint, S. D. (2019). Linkages between stratospheric ozone, UV radiation and climate change and their implications for terrestrial ecosystems. *Photochemical and Photobiological Sciences*, 18 681-716.

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library:
research-pubs@uow.edu.au

Linkages between stratospheric ozone, UV radiation and climate change and their implications for terrestrial ecosystems

Abstract

Exposure of plants and animals to ultraviolet-B radiation (UV-B; 280-315 nm) is modified by stratospheric ozone dynamics and climate change. Even though stabilisation and projected recovery of stratospheric ozone is expected to curtail future increases in UV-B radiation at the Earth's surface, on-going changes in climate are increasingly exposing plants and animals to novel combinations of UV-B radiation and other climate change factors (e.g., ultraviolet-A and visible radiation, water availability, temperature and elevated carbon dioxide). Climate change is also shifting vegetation cover, geographic ranges of species, and seasonal timing of development, which further modifies exposure to UV-B radiation. Since our last assessment, there has been increased understanding of the underlying mechanisms by which plants perceive UV-B radiation, eliciting changes in growth, development and tolerances of abiotic and biotic factors. However, major questions remain on how UV-B radiation is interacting with other climate change factors to modify the production and quality of crops, as well as important ecosystem processes such as plant and animal competition, pest-pathogen interactions, and the decomposition of dead plant matter (litter). In addition, stratospheric ozone depletion is directly contributing to climate change in the southern hemisphere, such that terrestrial ecosystems in this region are being exposed to altered patterns of precipitation, temperature and fire regimes as well as UV-B radiation. These ozone-driven changes in climate have been implicated in both increases and reductions in the growth, survival and reproduction of plants and animals in Antarctica, South America and New Zealand. In this assessment, we summarise advances in our knowledge of these and other linkages and effects, and identify uncertainties and knowledge gaps that limit our ability to fully evaluate the ecological consequences of these environmental changes on terrestrial ecosystems.

Keywords

climate, radiation, ecosystems, uv, terrestrial, ozone, stratospheric, between, linkages, implications, their, change

Publication Details

Bornman, J. F., Barnes, P. W., Robson, T. Matthew., Robinson, S. A., Jansen, M. A.K., Ballare, C. L. & Flint, S. D. (2019). Linkages between stratospheric ozone, UV radiation and climate change and their implications for terrestrial ecosystems. *Photochemical and Photobiological Sciences*, 18 681-716.

Authors

Janet F. Bornman, Paul W. Barnes, T Matthew Robson, Sharon A. Robinson, Marcel A.K Jansen, Carlos L. Ballare, and Stephan D. Flint

Chapter 3. Linkages between stratospheric ozone, UV radiation and climate change and their implications for terrestrial ecosystems

Janet F. Bornman^{*a}, Paul W. Barnes^{*a}, T. Matthew Robson^c, Sharon A. Robinson^d, Marcel A.K. Jansene^e, Carlos L. Ballaré^f, Stephan D. Flint^g,

^{*a}*College of Science, Health, Engineering and Education, Murdoch Univ., Perth, W. Australia.*

^{*b}*Department of Biological Sciences and Environment Program, Loyola Univ., New Orleans, USA.*

^c*Research Programme in Organismal and Evolutionary Biology, Viikki Plant Science Centre, Univ. of Helsinki, Finland.*

^d*Centre for Sustainable Ecosystem Solutions, School of Earth, Atmosphere and Life Sciences and Global Challenges Program, Univ. of Wollongong, Wollongong, NSW 2522, Australia.*

^d*Plant Ecophysiology Group, School of Biological, Earth and Environmental Sciences, UCC, Cork, Ireland.*

^e*Univ. of Buenos Aires, Faculty of Agronomy and IFEVA-CONICET, Buenos Aires, Argentina.*

^f*Dept of Forest, Rangeland and Fire Sciences, Univ. of Idaho, Moscow, ID, USA.*

Summary

Exposure of plants and animals to ultraviolet-B radiation (UV-B; 280-315 nm) is modified by stratospheric ozone dynamics and climate change. Even though stabilisation and projected recovery of stratospheric ozone is expected to curtail future increases in UV-B radiation at the Earth's surface, on-going changes in climate are increasingly exposing plants and animals to novel combinations of UV-B radiation and other climate change factors (e.g., ultraviolet-A and visible radiation, water availability, temperature and elevated carbon dioxide). Climate change is also shifting vegetation cover, geographic ranges of species, and seasonal timing of development, which further modifies exposure to UV-B radiation. Since our last assessment, there is increased understanding of the underlying mechanisms by which plants perceive UV-B radiation, eliciting changes in growth, development and tolerances of abiotic and biotic factors. However, major questions remain on how UV-B radiation is interacting with other climate change factors to modify the production and quality of crops, as well as important ecosystem processes such as plant and animal competition, pest-pathogen interactions, and the decomposition of dead plant matter (litter). In addition, stratospheric ozone depletion is directly contributing to climate change in the southern hemisphere, such that terrestrial ecosystems in this region are being exposed to altered patterns of precipitation, temperature and fire regimes as well as UV-B radiation. These ozone-driven changes in climate have been implicated in both increases and reductions in the growth, survival and reproduction of plants and animals in Antarctica, South America and New Zealand. In this assessment, we summarise advances in our knowledge of these and other linkages and effects, and identify uncertainties and knowledge gaps that limit our ability to fully evaluate the ecological consequences of these environmental changes on terrestrial ecosystems.

1 Introduction

The structure, function and diversity of terrestrial ecosystems are being modified by ongoing changes in the Earth's climate, and these complex changes are becoming increasingly evident with time.^{149, 257, 319} An assessment of the effects of depletion and recovery of stratospheric ozone and associated changes in ultraviolet-B radiation (UV-B, 280-315 nm) on the terrestrial biota must, therefore, consider the role of climate change in the response of these organisms and ecosystems. In some regions, stratospheric ozone depletion is itself contributing to climate change with the result that ecosystems are being affected by the consequent ozone-driven changes in temperature and precipitation (see Chapter 1 and ref.²⁷³). Prior assessments have considered the effects of stratospheric ozone depletion in the context of climate change and have reported on some of the ways in which climate change can potentially interact with ozone depletion and UV-B radiation to modify terrestrial ecosystem function and composition.^{26, 50, 61} Here, we report on progress made since the last Assessment.⁵⁰ and examine and further explore recent findings that document interactive effects of ozone depletion, UV-B radiation and climate change on terrestrial organisms and ecosystems, including cultivated species and highly managed ecosystems (e.g., agro-ecosystems). We emphasise effects that have, at least to some degree, been demonstrated to occur in nature, but also identify areas where potential effects on terrestrial ecosystems could occur in the future. Where possible, areas of uncertainty are addressed, and the significance of findings is placed in a context relevant to policy makers.

Ecologically significant linkages between stratospheric ozone depletion, climate change and UV radiation are diverse, sometimes bi-directional, and, in certain cases, exhibit important feedbacks to the climate system (**Fig. 1**). However, climate change is increasingly contributing to changes in the timing and duration of UV-B radiation exposure, independent

of changes in stratospheric ozone. These changes can occur in a number of ways (see section 7). One avenue involves climate change-driven shifts in cloud cover, which is increasing in some regions (usually wetter areas), while decreasing in others (usually drier regions) see Chapter 1 and ref.¹⁴⁹ Similarly, climate change-driven effects on vegetation (e.g., forest die-

back or shrub invasions) can increase or decrease the UV exposure conditions of understory plants and animals. As a result of warmer growth conditions and altered timing of seasons, many plants are initiating growth and flowering earlier in the year,^{74, 170} while certain animals are adjusting their timing of breeding and migration.^{53, 311} As UV-B radiation varies

seasonally (Section 7.2), a change in the timing of important life-cycle events can easily affect their exposure to UV-B radiation. In addition, the geographic ranges of many plants and animals, including wild and domesticated species, are shifting to higher elevations and latitudes in response to climate change.^{149, 253, 257, 291, 299} Because of existing natural altitudinal

and latitudinal gradients in solar UV radiation (see Chapter 1 and refs^{48, 62, 226}) these changes in geographic ranges can potentially increase (at high elevations) or decrease (at high latitudes) the amount of UV-B radiation received by organisms. Unlike ozone depletion, all of the above climate change-driven effects are modifying exposure of organisms to the full

solar radiation spectrum at the Earth's surface, including UV-B as well as UV-A (315-400 nm) and visible (400-700 nm) radiation. At the same time, plants and animals are being exposed to novel combinations of UV radiation with other abiotic (e.g., changing day length, and fluctuating temperatures) and biotic factors (e.g., competitors, pests, and pollinators).

Because of these complexities, it is necessary to consider how responses of organisms and ecosystems to UV-B radiation are modified by concomitant changes in other regions of the

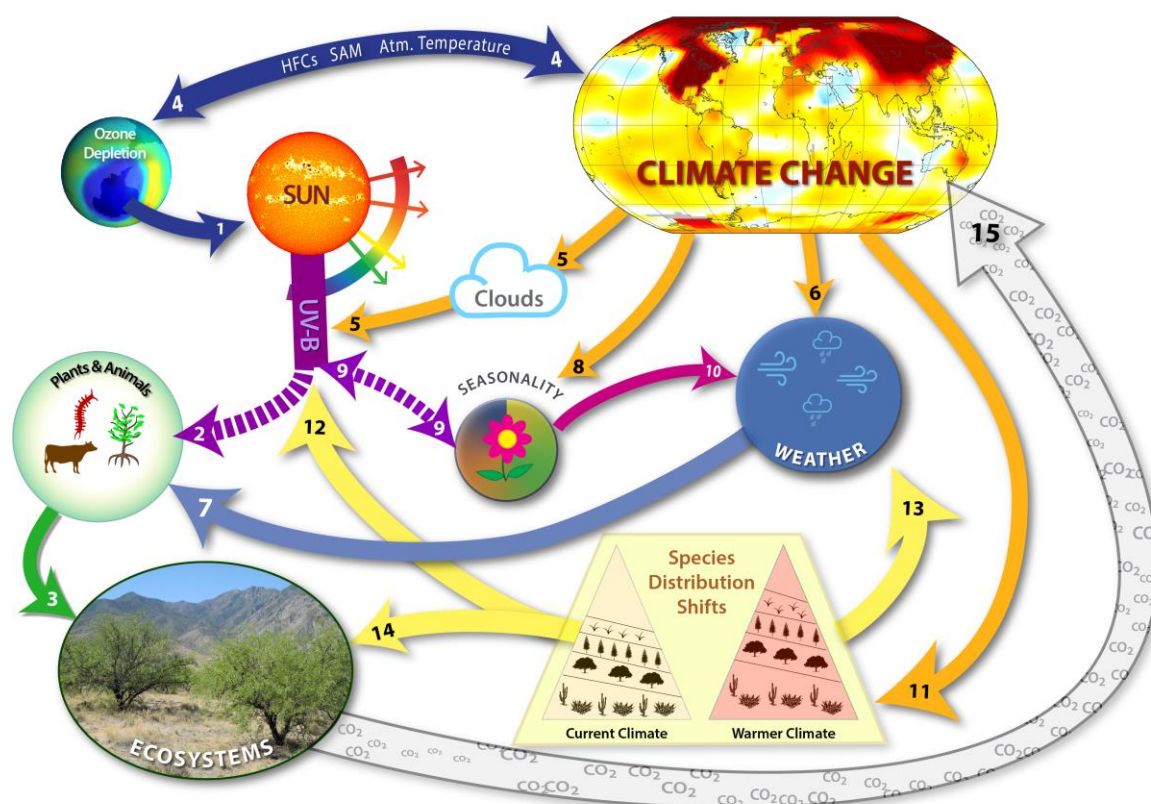


Fig. 1 Conceptual diagram illustrating known linkages between stratospheric ozone depletion, UV radiation and climate change on terrestrial organisms and ecosystems. Stratospheric ozone depletion alters UV radiation (primarily UV-B; arrow 1), which in turn directly affects plants and other organisms (arrow 2). The effects on organisms can then alter the function and structure of ecosystems (arrow 3). Ozone depletion can alter the climate, and climate change can affect ozone depletion via several avenues (arrow 4). Certain ozone-depleting substances (e.g., hydrofluorocarbons (HFCs) and others) are potent greenhouse gases that can enhance global warming. Stratospheric ozone depletion in the southern hemisphere is directly altering climate via changes in the Southern Annular Mode (SAM) in addition to other climate changes. Resultant shifts in climate zones alter regional rainfall and drought and thereby change cloud cover; in turn, the changing cloud cover can increase or decrease exposures of organisms to UV radiation (arrow 5). Climate-related changes in weather patterns (arrow 6) alter temperature and precipitation patterns, which can directly modify plant growth and development, and the way in which plants respond to UV-B radiation (arrow 7). Climate change (including altered UV-B exposure) is also changing the seasonal timing of development (e.g., phenology of flowering or bud break; arrow 8), such that wild plants and crops develop at times of the year when UV radiation can be either greater or less than prior to current rapid climate change (arrow 9). These phenological changes further expose plants to novel combinations of UV radiation and other abiotic and biotic factors (arrow 10). In response to climate change many organisms are shifting their ranges to higher elevations and latitudes (arrow 11). As with phenological shifts, these changes in geographic ranges can potentially increase (elevation) or decrease (latitude) exposures to UV radiation (arrow 12), as well as subjecting organisms to new combinations of UV radiation and other abiotic factors (arrow 13). As species migrate to different environments they also encounter new combinations of competitors, pests and pollinators that may alter important ecosystem processes such as herbivory and competition (arrow 14). Alterations in certain ecosystem processes, such as decomposition, can modify soil carbon storage and emissions of carbon dioxide and other greenhouse gases to the atmosphere (arrow 15). Image of stratospheric ozone shows total ozone over Antarctica (October 2017, Source: <https://ozonewatch.gsfc.nasa.gov/>). Climate change map indicates surface temperature anomalies for February 2017 compared to the base-period of 1951-1980 (Source: <https://data.giss.nasa.gov/>). Sonoran desert ecosystem photograph by P.W. Barnes.

solar spectrum (i.e., UV-A and visible radiation) as well as simultaneous changes in a diverse range of abiotic and biotic factors.

Solar UV radiation (UV-B and UV-A) is known to affect the growth and performance of terrestrial plants and animals (see sections 3 and 4). The shorter wavelengths of UV radiation (mostly in the UV-B range) may cause cellular damage, which can lead to changes in the morphology, physiology, and biochemistry of the organism. However, concurrent exposure to longer wavelengths (e.g., UV-A and/or visible radiation), can often reduce the negative effects of UV-B radiation.³²² In addition, both UV-B and UV-A radiation are important sources of information for plants and animals. This radiation is perceived by specific photoreceptors, which trigger a range of responses. Many animals sense UV radiation and avoid exposure to prolonged periods of high UV-B radiation.^{81, 222} These behavioural responses together with physiological mechanisms can mitigate some of the negative outcomes of high UV-B radiation. In some animal species (e.g., insects and birds), UV radiation is used as a visual cue that enhances foraging, mate selection, or other behavioural activities.⁸¹ By comparison, land plants are sessile (rooted to their growth medium) and require sunlight for photosynthesis and growth. Their primary response to changing UV radiation conditions typically involves acclimating or adapting to these changes using biochemical and physiological mechanisms. However, like animals, plants can sense UV radiation in their surroundings, which has adaptive value.¹⁵⁹

Following the discovery of the Antarctic ozone hole, many initial studies (as reviewed in refs^{11, 32, 46}) emphasised the direct detrimental effects of increased UV-B radiation on plants, especially important food crops. However, most evidence to date indicates that, under realistic exposures, the direct, damaging effects of high UV-B radiation on photosynthesis, plant productivity and crop yield, are relatively minor.^{26, 110, 155, 240, 283, 336} More recent studies have focused on understanding how plants a) respond to UV radiation against the backdrop of a rapidly changing climate in conjunction with current and projected stratospheric ozone dynamics; and b) perceive the UV-B radiation and what role this radiation plays in regulating growth and development.^{44, 160, 162, 356} At present, it is widely accepted that UV-B radiation can have beneficial as well as unfavourable effects on plants.^{156, 208, 239, 336} In some cases, reduced exposure to UV-B radiation can even have negative consequences for plant growth, defence against pests,²⁷ and food quality.²⁰ Thus, projected recovery of stratospheric ozone to levels that may exceed those in the recent past (i.e., 1970's; Chapter 1 and ref.²⁵⁶), means that there is a need to fully evaluate how organisms and ecosystems will respond to the increases and decreases in solar UV-B radiation that occur in conjunction with a rapidly changing climate.

Climate change alters regional weather patterns, including temperature and precipitation, and these changes can directly affect plants and ecosystems by altering moisture availability and critical thermal conditions for growth, reproduction, and survival. Of interest in this assessment, however, is how plant responses to climate change are modified by UV radiation (see section 3). Exposure to UV-B radiation can enhance plant tolerance to some abiotic factors (e.g., water and temperature stress),²⁷⁵ while other factors may alter the sensitivity of plants to UV radiation. However, these effects are complex and often dependent upon specific growth conditions.²¹⁷ Understanding how plants respond to changes in UV radiation against this backdrop of changes in multiple environmental variables is thus challenging but necessary in the context of future environments (e.g., ref.³²⁶). These UV-climate change interactions are particularly relevant for agroecosystems, where changes in crop yield, food quality, resistance to pests and diseases, and overall vulnerability of plants to climate change can have significant impacts on food security (see section 5).

The effects of changes in incident solar UV radiation (UV-B and UV-A) on ecological communities and ecosystems are largely a consequence of impacts on primary producers (i.e., plants).^{25, 63, 335} These higher-level ecological effects include changes in plant-plant

interactions (competition), herbivory, pest-pathogen interactions and the decomposition of dead plant matter (litter) (see section 6). Although initially minor, some of these community- and ecosystem-effects may accumulate over time (e.g., ref.²⁷⁶) or be amplified by processes such as competition.³⁷ For certain crop species, exposure to UV radiation can elicit changes in pest/pathogen defence that may have positive consequences for the productivity and sustainability of agroecosystems.^{25, 27, 335}

One important ecosystem-level effect of changes in UV radiation and climate is the altered decomposition of plant litter, which can result in a positive feedback to the climate system, thereby contributing to climate change. Photodegradation is the process whereby UV radiation, together with shorter wavelengths of visible radiation, drives the photochemical break-down of plant litter, and this results in the release of carbon dioxide and other gases to the atmosphere (see section 6.3, Chapter 5 and refs^{54, 181}). Photodegradation can also modify the chemical make-up of litter, thereby promoting or facilitating the activities of microbial decomposers (bacteria and fungi; i.e., photo-facilitation). This results in increased microbial and soil respiration, and contributes additional carbon dioxide to the atmosphere.^{17, 22, 279} At present, considerable uncertainty remains regarding the quantitative significance of photodegradation of terrestrial plant litter, and its effects on storage of carbon in soil and concentrations of atmospheric CO₂. However, it is clear that this process is an important driver of decomposition in many ecosystems, especially drylands (grasslands, deserts, and savannas).^{3, 17} In some of these dryland ecosystems, the relative importance of UV-driven photodegradation may increase with climate change as precipitation decreases and temperature increases.⁵ Changes in climate and land-use may also affect photodegradation and litter decomposition indirectly via changes in the structure and species composition of vegetation, and occurrence of fire and soil erosion (see section 6.3 and Chapter 5).

There are several linkages between ozone depletion and climate change that are ecologically important but which do not directly involve changes in UV radiation. On the one hand, climate change can modify stratospheric ozone depletion by perturbing temperature dynamics between the stratosphere and troposphere.¹³ Conversely, it is now apparent that stratospheric ozone depletion in the southern hemisphere is directly contributing to climate change (**Fig. 2**) (see Chapter 1) Specifically, ozone depletion appears to be changing patterns of regional atmospheric circulation in the southern hemisphere which, in turn, affect weather conditions, sea surface temperatures, and frequency of wildfires.^{75, 143, 171, 188, 248} These changes together with changes in UV-B radiation can have several consequences for terrestrial ecosystems (see section 2, **Table 1**, and ref.²⁷³) While ozone depletion in the northern hemisphere may be associated with similar, but smaller, climate shifts (Chapter 1), to our knowledge, there are no reports linking this to ecological impacts.

Finally, a better understanding of how terrestrial organisms and ecosystems might respond to changes in UV radiation in the context of modern climate change is coming from studies examining how plants and animals have adapted to changing UV radiation and climate conditions in the past. These historical studies, however, require some knowledge of how UV radiation has changed over geological time periods. In the absence of satellite or ground-based measurements of UV radiation, some investigators have attempted to reconstruct past UV radiation climates using biological indicators as proxies for ground-level UV radiation. Section 8 evaluates progress made in the development of pollen grains and spores as bioindicators of past UV conditions.

2 Ecological effects of ozone depletion on climate in the southern hemisphere

Stratospheric ozone depletion has led to large changes in the climate of the southern hemisphere (as detailed in Chapter 1 and refs^{50, 273}). These are manifested in a mode of atmospheric variability, the Southern Annular Mode (SAM or Antarctic oscillation), which describes the difference in pressure between 60° and 45° S. The SAM describes the strength and latitudinal position of the westerly wind belt (i.e., jet stream) around Antarctica (see also refs^{50, 273}). Ozone depletion is linked to a highly positive phase of the SAM,^{2, 135} corresponding to an increased pressure difference between mid- and high latitudes and a contraction of the westerly wind belt towards Antarctica (**Fig. 2**). The effects of this change in atmospheric circulation, which extend across the southern hemisphere, are summarised in the following sections. The sections emphasise how these changes in climate link to stratospheric ozone

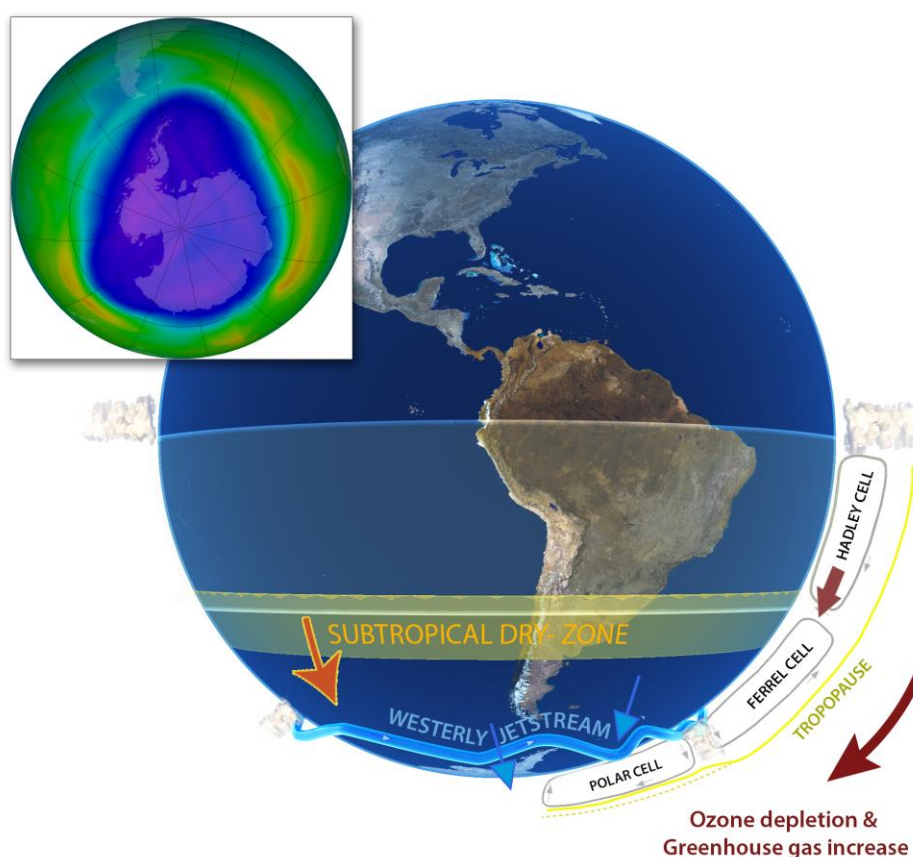


Fig. 2 The Antarctic ozone hole (inset) and its impact on southern hemisphere atmospheric circulation. Stratospheric ozone depletion and resultant cooling over Antarctica has caused the tropopause to lift, allowing the Hadley Cell (dark red arrow) and the westerly jet stream to tighten and shift towards the South (blue arrow). The speed of the jet has also increased (see ref.²⁷³ for details). The polar shift in the jet and its increased strength changes atmospheric and oceanic circulation throughout the southern hemisphere consistent with a more positive phase of the Southern Annular Mode (SAM; see text for explanation). Over the past century, increasing greenhouse gases and then ozone depletion over Antarctica have both pushed the SAM towards a more positive phase, and the SAM index is now at its highest level for at least 1000 years.² As a result, high latitude precipitation has increased and the mid-latitude dry zone has moved south (orange arrow). As the ozone layer recovers, increased greenhouse gas forcing will likely take over and the position of the jet is thus predicted to remain in this more southerly location. Figure adapted from refs^{258, 273}, with ozone ‘hole’ over Antarctica, 17th September 2006, reproduced from NASA Ozone Watch.²³⁶

depletion (see also Chapter 1), affect abiotic drivers (e.g., wildfires) and the contingent responses of southern hemisphere ecosystems. The implications of these climate shifts for marine and aquatic ecosystems are described in Chapter 4.

Changing concentrations of stratospheric ozone have been linked to changing surface temperatures, altered wind and ocean circulation patterns and changing precipitation patterns, causing increased rainfall or drought, the latter leading to increased risk of wildfires. As presented in our last assessment, terrestrial⁵⁰ and aquatic ecosystems²⁷³ including biogeochemical cycling¹⁰³ have been affected by these changes across the southern hemisphere. Sections 2.1 and 2.2 give a brief summary of the climate changes ascribed to ozone depletion and then address the implications of these changes for ecosystems in the southern hemisphere.

The UNEP Science Assessment Panel (SAP)³⁴⁶ notes that since their last assessment,³⁴⁵ further research has confirmed the impact of changes in stratospheric ozone on the tropospheric and surface climate of the southern hemisphere and has, in some cases, allowed better quantification and attribution of the changes. Stratospheric ozone depletion is assessed to have been the dominant driver of changes in atmospheric circulation across the southern hemisphere from the mid-latitudes to the tropics during austral summer (December-February) over the period 1960 to 2000 when stratospheric ozone was decreasing; while in other seasons, greenhouse gas emissions play a comparable role to stratospheric ozone depletion. As stratospheric ozone recovers, its effect on circulation should diminish; however, climate change is predicted to increasingly contribute to changes in atmospheric circulation Chapter 1 and refs.^{93, 294}

The major changes in mid-latitude and tropical circulations driven by stratospheric ozone depletion include the poleward shift of the mid-latitude jet (**Fig. 2**), the shift to an increasingly positive phase of the Southern Annular Mode (SAM) and the poleward shift of the subtropical Hadley Cell (**Fig. 2**).^{20, 306, 346} Between 1980 and 2000, the westerly jet shifted south during summer by approximately one degree of latitude. Since 2000, the jet has shifted north in summer, although this reverse trend is not statistically significant.^{151, 346} A meta-analysis³³⁸ supports stratospheric ozone depletion as the dominant driver of the Hadley Cell summertime expansion over the period 1979 to late 1990s.

2.1 Changes to southern hemisphere regional rainfall related to stratospheric ozone depletion, and ecosystem responses to fluctuating availability of water, extreme rain, drought and fires

Changes in both extratropical and sub-tropical austral summer rainfall have previously been linked to the position of the mid-latitude jet and thus to stratospheric ozone depletion (**Figs 2, 3** and see Chapter 1 and refs^{50, 69, 131, 273, 345}). South-East South America (northern Argentina, Uruguay, southern Brazil and Paraguay) has experienced one of the largest increases in rainfall worldwide (**Fig. 3**; Table 1A)¹²¹ with a 30% increase in summer rainfall over the past 50 to 100 years. While this increased rainfall appears to be the result of anthropogenic emissions of greenhouse gases,^{96, 320} the relative contributions from greenhouse gases and ozone depletion to these changes have not yet been resolved (see also refs^{352, 359}).

The SAM has been identified as the leading cause of changes in summer rainfall, surface temperature, and the diurnal temperature range in East Africa^{206, 207}, and these authors highlighted the effects of stratospheric ozone depletion. Over the period 1961-1996, the position for the South Pacific Convergence Zone (a region of abundant precipitation, stretching from New Guinea towards southern hemisphere mid-latitudes) has changed, with increasing rainfall on the northern edge and decreases to the south.⁵⁸ This shift in precipitation appears related to concentrations of stratospheric ozone, with models suggesting a reversal of these effects

as stratospheric ozone recovers.⁵⁸ These shifts in rainfall patterns can have negative and positive effects on ecosystems, populations and individual species.

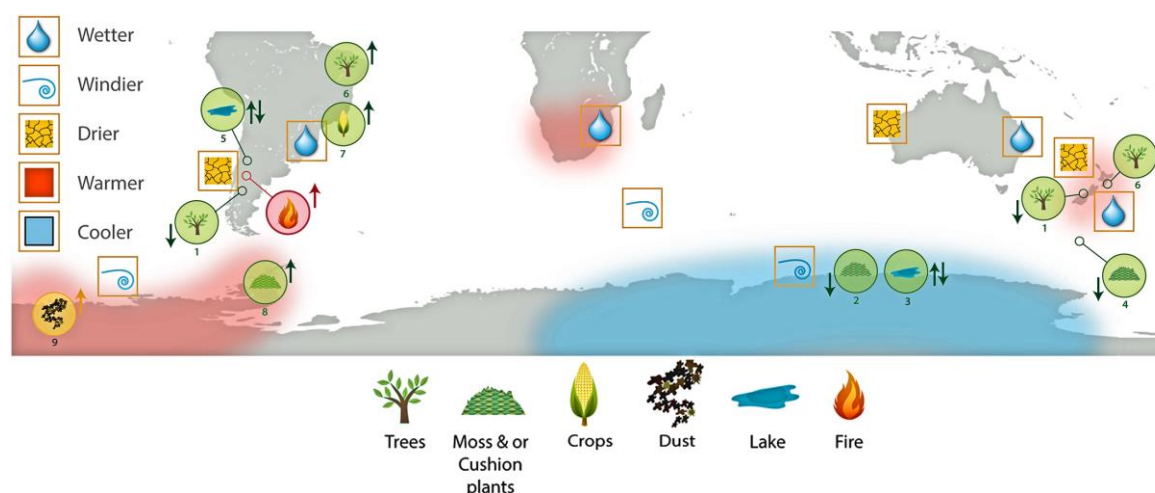


Fig. 3 Map of the southern hemisphere showing how stratospheric ozone depletion affects the climate and environment, and the effects of these abiotic changes on terrestrial ecosystems and populations. Symbols show types of organism, ecosystem or entity affected (see legend), with numbers referring to Table 1C, which provide species and location details. Arrows indicate direction of effects on biodiversity, up = positive, down = negative effects, two-way arrows indicate changed biodiversity.

Table 1 Summary of how stratospheric ozone depletion affects the climate and environment (A) likely consequences, (B) the effects of these abiotic changes on terrestrial ecosystems, and (C) populations across the southern hemisphere. Regions affected, and references are provided. Numbers (C) refer to locations in Fig. 3.

A.	Regional examples	References
Changes in southern hemisphere climate driven by stratospheric ozone depletion		
<u>Changing regional precipitation</u>		Chapter 1 and refs ^{19, 93}
Wetter	South East South America (Northern Argentina, Uruguay, southern Brazil and Paraguay)	Refs ^{121, 165}
Wetter/Drier	New Guinea, southern hemisphere mid-latitudes wetter in the north and drier to the south Hydroclimatic variability over the Amazon Basin	Refs ^{58, 199}
Drier	Chile, declining stream flows, consequences for ecosystem health and hydroelectric power	Ref. ²³⁵
More extreme precipitation	South-eastern South America extreme Summer rainfall	Refs ^{121, 164, 187, 265, 352}

A.	Regional examples	References
Changes in southern hemisphere climate driven by stratospheric ozone depletion		
	Heavy rain events in Madagascar	
<u>Changing ocean and atmospheric circulation</u>		Chapter 1 and ref. ⁹³
Shifting location of wet and dry zones	Shifts in summer rainfall patterns, Australian summer - increased rainfall on mainland south east coast and decreased rainfall in western Tasmania. Sub-tropical dry zone also shifted towards the South Pole	Refs ^{30, 132, 150, 206, 265, 287, 306}
Increasing surface wind-stress	Southern Ocean Leads to year-round stronger surface ocean warming Could enhance loss of Antarctic sea ice but see Chapter 1. Alters mixed layer depth affecting nutrients	Chapter 4 and refs ^{94, 141, 295}
<u>Temperature</u>		Chapter 1 and ref. ⁹³
Lower temperatures	Decrease in summer temperatures over East Antarctica, southeast and south-central Australia and inland areas of the tip of southern Africa. Eastern Tropical Pacific cooler	Refs ^{30, 75}
Warmer temperatures	Much of Southern Africa warmer Warmer surface temperature and changed diurnal temperature range in East Africa Summer extreme temperatures, Australia, South America, Southern Africa	Refs ^{30, 206}

B.	Resulting from	References
<u>Likely indirect consequences of changes in southern hemisphere climate</u>		
Changing cloud patterns	Latitudinal shifts in the Hadley and Polar Cells mean that cloud cover has also shifted southward with ozone depletion	Ref. ²⁸⁷ See Chapter 1 for implications for exposure to UV radiation
Fire	Changes in precipitation can alter fire regimes; e.g., central and southern Chile	See Chapter 5 and refs ^{143, 144, 210}
Dissolved organic matter (DOM)	Changes in precipitation affect run off and quantity of DOM in water bodies	See Chapter 4 for details
Breakdown of litter	Changes in precipitation and temperature influence breakdown rates of litter	See Chapter 5 for details
Air quality	Weather [temperature, wind (transporting pollutants), rain and cloudiness] affects air quality with consequences for health	See Chapter 6 for details

B. <u>Likely indirect consequences of changes in southern hemisphere climate</u>	Resulting from	References
	of humans, other animals and plants	
Weathering of materials	Increased ambient temperature shortens the life of plastics and wood exposed to UV radiation, and their outdoor service life-times. Changing moisture also affects these processes	See Chapter 7 for modes of action

C. Drivers of change for terrestrial plants and ecosystems (number of marker on Fig. 3)	Biological effects	Location	References
Decreased water availability			
1	Less precipitation associated with decreasing growth of trees and restricted forest distribution	West New Zealand, South West S. America	Refs ^{82, 325}
2	East Antarctic drying. Moss beds exhibit changing species composition. Reduced growth, more plant stress and death.	Windmill Islands, East Antarctica	Refs ^{73, 140, 274}
3	Lakes are becoming more saline leading to biodiversity changes		
4	Drying caused more than 80% dieback of cushion plant and moss fellfield communities	Macquarie Island	Refs ⁴¹
Increased water availability			
5	Less salinity causes changes in lake fauna	Eastern side of the Andes	Ref. ⁸⁰
6	More precipitation associated with increasing growth of trees	East New Zealand, Eastern South America	Ref. ³²⁵
7	Expansion of agricultural zones with more precipitation	South East S. America	Refs ^{121, 124}
8	Moss beds and other biodiversity more productive due to warmer wetter conditions and more land	Antarctic Peninsula	Refs ^{8, 277, 357}
Increased wind speeds			
9	Risk of increased dust and potential propagule inputs into Antarctica (negative if introduces non-native species)	West Antarctic, Antarctic Peninsula	Refs ^{68, 116, 219, 223}

2.1.1 Ecosystem responses to fluctuating water availability

Shifting atmospheric circulation cells (Hadley, Ferrel, and Polar cells, see **Fig. 2**) alters regional precipitation across the southern hemisphere, causing some areas to receive more moisture and others to become drier. In Patagonia, declines in tree growth have been linked to reduced water availability (Fig. 3; Table 1B).³²⁵ In the extreme south of South America extending into Antarctica, lichens are an increasingly-dominant component of the terrestrial biota.⁷⁸ Lichens are extremely tolerant of desiccation, but nevertheless the combination of high wind speeds and high irradiance, including increased UV-B radiation due to ozone depletion, have been shown to affect their colonisation on trees in Patagonia.³¹³ However, lichens grow very slowly,⁷⁹ so responses to specific climatic changes can take a long time to detect. Less seasonal precipitation and a reduced diurnal temperature range were the dominant factors driving aridity and limiting the distribution of high-elevation woodlands of *Polylepis tarapacana* (a rose-family species of tree of high conservation value, found in the South American Altiplano). Models predict that by the end of this century almost half of the potential range of this species will be lost due to increased aridity.⁸²

Decreased precipitation in this region of South America has led to reduced stream flows in Chile, with adverse effects on aquatic and terrestrial ecosystems as well as the production of hydroelectric power.²³⁵ Since the 1960s, warming and associated drying at mid- and high-latitudes to the west of the Andes have resulted in increased forest fires (measured from fire scars in tree ring records).¹⁴³ During the 2016–2017 fire season, more than 500,000 hectares burned in central and southern Chile (between ~29°S and 40°S), driven by a long-lasting drought linked to the positive SAM that was amplified by conditions resulting from the El Niño–Southern Oscillation (ENSO). Given that the positive phase of SAM is predicted to continue, it is likely that the increased frequency of wildfires in southern South America will continue throughout the 21st century.¹⁴³

Several other regions of the southern hemisphere have experienced wetter summers (Chapter 1), leading to increased tree growth in eastern New Zealand³²⁵ and expansion of agriculture in south-eastern South America (Fig. 3; Table 1B).¹²¹ The eastern side of the Andes has experienced wetter conditions with associated changes in biodiversity. For example, changes in fauna (ostracods and chironomids) from lake sediments in El Toro Lake (40°S, 70°W) indicate that the lake has become fresher (less salty) as a result of increased precipitation since the middle of the 20th century, associated with the positive phase of SAM.⁸⁰

Increasing extremes of precipitation have also been linked to SAM-related changes. Rainfall patterns in the southern Amazon Basin have been reconstructed from tree rings of *Centrolebium microchaete*¹⁹⁹ and the findings suggest that the fluctuations between drought and extremely wet seasons seen from 1950 to the present day may be unmatched since 1799.

2.2 Changes in surface temperatures because of stratospheric ozone depletion and implications for terrestrial ecosystems

Recent studies^{72, 292} suggest that warming of West Antarctica and the Antarctic Peninsula may fall within the range of natural climate variability.¹⁶¹ This warming had previously been linked to anthropogenic emissions of greenhouse gases and stratospheric ozone depletion.^{50, 273} Stratospheric ozone depletion could account for between a quarter and one third of summer and autumn cooling over the rest of the Antarctic continent (see ref.²⁷³). However, our confidence in any attribution or projections of climate warming over this region is limited by the large biases inherent in the models used. Depletion of Antarctic stratospheric ozone has possibly offset a substantial portion of the summer warming that would otherwise have occurred (due to increasing greenhouse gases) in eastern Australia, southern Africa and South

America (**Fig. 3**).³⁰ These changes in temperature are likely to have affected (positively and negatively) life cycles of plants and animals, potentially leading to mismatches between plants and their pollinators (see section 7.3). Cooler temperatures over East Antarctica have likely slowed the melting of ice sheets. As stratospheric ozone recovers, the extent of this amelioration may be reduced with potential implications for the climate and populations of these regions as well as further afield.

In western Antarctica, along the Antarctic Peninsula and on nearby islands, increasing temperatures⁷⁵ were associated with increased productivity of terrestrial ecosystems (microbial productivity, plant growth rates and carbon accumulation in moss beds) from the 1950s to the turn of the century.⁸ There is some evidence that the direction of these changes has reversed since 2000, consistent with recent cooling in this region.^{8, 247, 315} However, as noted above, the relative contributions of stratospheric ozone depletion *vs* increasing greenhouse gases to temperature changes is still unresolved because recent studies suggest they are not beyond the range of natural variability (see above and Chapter 1).

In the Windmill Islands of East Antarctica, decreased water availability since the 1960s, linked to decreasing temperatures and increasing wind,⁷³ has resulted in changes in biodiversity in Antarctic moss beds²⁷⁴ and lakes,¹⁴⁰ with species composition changing to reflect the newly drier moss beds and more saline lakes. In addition, these East Antarctic plant communities are becoming more stressed as a result of drying, resulting in increasingly moribund moss.^{204, 205, 274} This is one of the first studies²⁷⁴ to document ecosystem-level changes in Antarctic terrestrial plant communities, which are correlated with the SAM and potentially linked to stratospheric ozone depletion and climate change. Further north, widespread (> 80%) dieback of cushion plants (*Azorella macquariensis*) and mosses, on sub-Antarctic, Macquarie Island, was primarily attributed to reduced water availability because of higher wind speeds, more sunshine hours and therefore higher evapotranspiration since the 1970s. The authors estimated that, from 1992 to 2008, these plant communities suffered accumulated water deficit for 17 years.⁴¹ This dieback of Antarctic and sub-Antarctic vegetation is similar to the “*Arctic browning*” observed in the Arctic in response to extreme climate events.^{102, 261}

2.2.1 Interannual variability

Two studies have linked interannual variability of springtime Antarctic ozone to summer changes in surface temperature and rainfall in the southern hemisphere.^{30, 296} The SAP 2018 report³⁴⁶ concludes that interannual variability in springtime ozone at both Poles may be important for surface climate, but the extent of this connection is not fully understood.

Stratospheric ozone-driven climate change has widespread and far-reaching effects on terrestrial and marine ecosystems (see Chapter 4) across the southern hemisphere. A better understanding is needed of the relative contributions of stratospheric ozone, greenhouse gases and interannual variability to determine the ecological or biological change attributable to stratospheric ozone depletion *vs* that due to these other climate factors. Nevertheless, we have only included studies in this section where a strong signal of ozone depletion or summer SAM has been associated with an ecological effect.

3 Plant response to UV radiation and interactions with climate change

There is now a basic understanding of UV-sensing and UV-signalling in plants, as well as the consequences for gene-expression, physiology, biochemistry, plant growth, fitness and nutritional quality. Potentially, UV-B radiation can damage plants through effects on DNA, the photosynthetic machinery, and other cellular targets. However, UV-B-induced

plant defence responses, including up-regulation of photorepair processes, antioxidant capacity, and UV-screening, are thought to be effective in the prevention of damage to plants by UV-B radiation under most natural conditions. Nevertheless, effective prevention and repair do not imply that UV radiation has no effect on plants. Acclimation to UV radiation and climate change factors can modify plant growth and development, which, in turn, has consequences for ecosystem functioning (section 6), nutritional quality and food security (section 5). Thus, understanding plant response to UV radiation and some of the interactive effects of climate, is of fundamental importance for evaluating effects of UV-B radiation on terrestrial ecosystems.

3.1 Limitations to current studies investigating interactive effects

Much of our understanding of plant responses to UV radiation began with single-factor experiments in laboratories, greenhouses, and controlled environment chambers that did not account for interactive effects from multiple climatic variables. Overall there is evidence that conditions in artificial environments may unrealistically accentuate the negative effects of UV-B radiation on plant growth. For instance, such studies are often conducted in growth chambers or greenhouses where lamps are used as the principle source of UV-B radiation and the ratio of UV-B radiation to photosynthetically active radiation (PAR, 400-700 nm) is far above that generally found in field conditions. We illustrate these limitations for some recent controlled-environment studies (**Fig. 4**). Note that only 16 of the 49 studies surveyed provided enough UV and PAR data to be represented as data points in the figure.

It is important to use the knowledge from these studies to design experiments for testing the results at more expansive scales of space and time. Laboratory results may be scaled up by progressively moving to more realistic conditions in controlled environments and then to field experiments (e.g., ref.¹¹¹). Another scaling approach is to design experiments

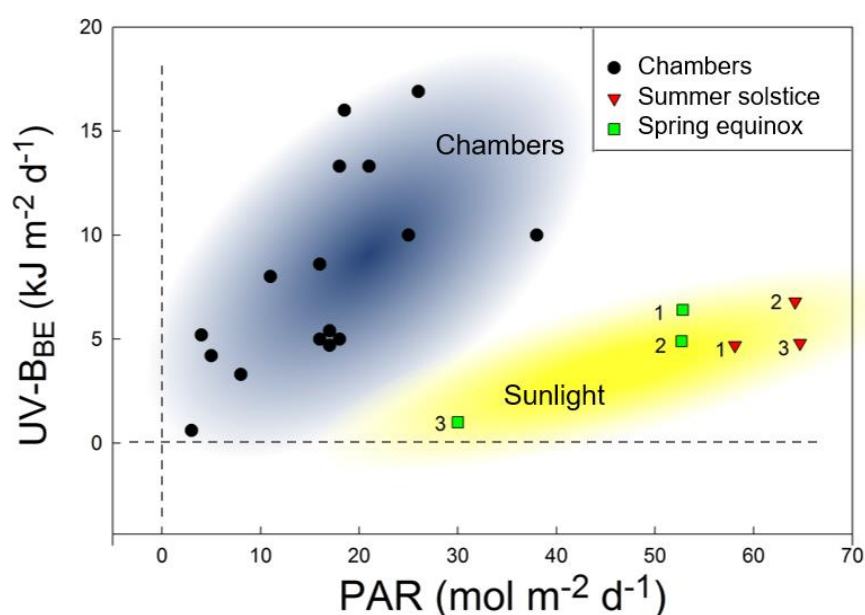


Fig. 4 Studies conducted in growth chambers (blue) are still using unrealistic ratios of photosynthetically active radiation (PAR, 400-700 nm) to biologically effective UV-B radiation (UV-B_{BE}; data were reported using the generalized plant action spectrum of Caldwell et al.⁶⁰ (more commonly used in these studies than the action spectrum of Flint et al.¹¹³) compared with natural sunlight (yellow). Growth chamber experiments are represented by black circles within the blue shading. Solar irradiances within the yellow shading represent the summer solstice (red triangles) and spring equinox (green squares). Ambient PAR is from ²⁷⁰ and ambient UV-B_{BE} was computed with the TUV calculator: http://cprm.acom.ucar.edu/Models/TUV/Interactive_TUV/. Latitudinal locations are indicated by numerals: 1. Equator (0°), 2. Tropic of Cancer (23°N), and 3. 55°N. A total of 49 peer-reviewed papers on growth chamber studies from the years 2011-2017 were surveyed; 16 are represented as data points in this figure and 33 could not be represented, because they either lacked radiation data or it was not measured in a manner comparable to the other studies.

moving from our common organism-centered methodology to a community or ecosystem perspective, where interactions, feedbacks, and their relative magnitudes under realistic conditions are examined.¹⁰⁸ Some recent studies have investigated the effects of UV-B radiation in combination with other variables related to climate change, such as drought, temperature, carbon dioxide, and tropospheric ozone (e.g., refs^{209, 216, 342}). For this assessment, we evaluated the experimental studies and methodological protocols,¹⁰ resulting in the exclusion of some studies in our summary findings.

3.2 The UV-B photoreceptor and signalling pathways

The existence and nature of a specific UV-B photoreceptor in plants, the protein, UVR8, initially came to light in 2011.²⁷¹ Since this discovery, a basic understanding of UV-sensing, signalling and function has emerged that has improved our knowledge of the molecular mechanisms underlying UV defence and acclimation in plants.^{159, 271, 356}

UVR8-mediated perception of UV-B radiation contributes to up-regulation of the expression of genes that encode components of the phenylpropanoid biosynthesis pathway, photorepair of DNA damage, and enhanced antioxidant capacity.¹⁵⁹ Penetration of UV-B radiation into leaves depends on the concentration of flavonoids and other phenolics in the epidermis, as well as plant anatomical and morphological characteristics that vary among species. Most of the UV-B radiation is strongly attenuated as it passes through the epidermis, although it has been measured in some herbaceous plant species in deeper-lying tissues (mesophyll layers), with 18-41% epidermal transmittance.^{51, 86} Given that the UVR8 protein has been detected in most plant tissues investigated, including roots, it is currently difficult to pinpoint in which plant tissues perception of UV-B radiation takes place in plants growing in sunlight. Tissue-specific analysis of UVR8 activity has revealed that the UV-B-induced UVR8 signalling pathway in epidermal and mesophyll cells is involved in hypocotyl elongation, while UVR8 expression in the epidermis contributes to cotyledon expansion.⁴² Thus, the UV-B-induced response appears to be partly mediated by tissue-autonomous signalling, although inter-tissue signalling may also be involved.⁴² The role of UVR8 is not simply limited to protection from UV-B radiation. There is now strong evidence that UVR8-mediated signalling extends to processes such as stomatal function, de-etiolation (greening response of plants), entrainment (alignment with) the circadian clock, phototropism, and defence against pathogens.³⁵⁶ These findings, mainly on the model plant, *Arabidopsis thaliana* (a type of cress), provide a frame of reference for the study of the multifaceted role of UV-B perception through photoreceptor(s) in the regulation of plant growth and development in the much more complex natural environment. This frame of reference can also be used for other plant species that are likely to follow a variety of strategies to acclimate and adapt to their habitats.

While much attention has been given to elucidating UVR8-mediated processes, UVR8 is not the only UV-B sensing mechanism in plants. There are also UVR8-independent signalling pathways,¹⁸⁵ for example, arising from oxidative stress and via UV-B-mediated DNA damage,⁴³ including generation of cyclobutane pyrimidine dimers (CPD, one of the main types of DNA damage). However, CPD photolyase, which repairs the damage, is predominantly regulated in a UVR8-dependent manner in plants exposed to UV-B radiation. There is evidence that the UVR8-mediated signalling pathway regulates the scavenging capacity of reactive oxygen species (ROS),¹³⁸ and the production of nitric oxide in response to UV-B-induced stress.³¹² These latter molecules may themselves play a role in signalling.³¹²

Thus, plant response to UV-B radiation likely involves multiple UV-signalling pathways. Moreover, components of these UV-mediated signalling pathways interact with other stress-

induced signalling pathways, such as those activated by other wavelengths of light, exposure to drought, extreme temperatures, and other factors associated with climate change.

3.3 UV-B-mediated signalling, crosstalk and cross-tolerance

There is still a lack of information and understanding concerning the effects of UV-B radiation in a complex environment where plants are simultaneously or sequentially exposed to multiple environmental factors that can modify plant growth and development.

In principle, the simultaneous application of treatments involving changes in two environmental factors can lead to additive, synergistic, antagonistic, or no effect. It is particularly relevant from an agronomic perspective that acclimation responses induced by changes in one environmental factor can confer cross-tolerance (including priming responses) or cross-sensitivity to another factor. Exchange of information between distinct plant-signalling pathways can broaden the spectrum of responses to one environmental factor. For example, high levels of PAR and UV-B radiation generally increase the accumulation of flavonoids, with synergistic effects occurring in some cases when plants are exposed to a combination of both variables.^{35, 234} Such increases of protective pigments with antioxidant activity potentially enhance the tolerance of a plant to a variety of unfavourable conditions.

Cross-talk also occurs when UV-B-mediated signalling cascades interact with signalling pathways induced by biotic variables, e.g., bacteria. This cross-talk can sometimes lead to a shift in other plant defences at the expense of the UV-induction of protective mechanisms, such as the accumulation of flavonoids.¹⁵ In this case, the UV-B-induced genes of the flavonoid pathway are suppressed by the bacterial elicitor, flg22 (a peptide), which, in turn, drives the immune response against the bacterium³⁶¹ by stimulating pathogen-protective compounds called phytoalexins. In other cases, UV-B radiation can increase plant resistance against pathogens and pests, by increasing the accumulation of metabolites involved in plant defence against multiple stress factors (reviewed in ref.²⁴). Other examples of cross-talk where UV-B radiation is implicated in plant stress responses include changes in some plant hormones, such as auxin, cytokinin, gibberellic acid, brassinosteroids, and jasmonic acid.^{109, 186, 281} UV-cross-talk involving the hormone abscisic acid can result in increased plant tolerance to water stress, extreme temperatures, or salinity. Some of these aspects are evaluated in the next section.

The interactions between UV-signalling and other signalling pathways imply that subtle molecular effects of UV-B radiation may potentially extend to many aspects of growth and development, with implications for ecosystems including agricultural systems under conditions of current and future climate change.

3.4 Plant and ecosystem response to potential interactive effects of UV-B radiation and climate change factors

Exposure to changing environmental conditions can directly affect plant growth and may also drive changes in phenology (section 7.3) and shifts in the distribution ranges of species (section 7.1). Here we will specifically explore interactions between UV-B radiation and certain key abiotic climate variables. In comparison to studies on interactive effects of UV-B radiation and drought and/or temperature, far less is known about interactive effects of UV-B radiation and elevated CO₂ on plants.

3.4.1 UV radiation and drought

The potential for plant responses to UV radiation and drought to reinforce each other has been the subject of research because seasonal droughts are usually coincident with, or

follow, periods of prolonged sunny weather, implying high exposure to UV radiation. An example of such synergies comes from an experiment with seedlings of silver birch (*Betula pendula* L.) subjected to treatments combining solar UV-B radiation and water stress outdoors in southern Finland. In this investigation, leaf and whole plant water potential responded to the combination of ambient UV-B radiation, conferring resistance to drought, which was visible through reduced wilting and lower mortality beyond that of UV-B radiation or water stress alone.²⁷⁵ Plant response to the combinations of UV-B radiation and drought should be considered when selecting agricultural crops because of potential consequences for crop quality.²¹⁵

Additional research provides evidence for synergies in response to drought and UV-B radiation.^{134, 172} However, both the mechanisms and outcome of response to combinations of water stress and UV-B radiation are often inconsistent. To some extent, the seemingly contradictory results reflect differences among studies in the timing and levels of drought and UV-B radiation applied to the plants. Sequential exposure to two environmental variables can allow the first to elicit a response that primes the plant for the second, resulting in cross-protection. In contrast, simultaneous exposure may weaken plant defences.³¹ In this context, it should be noted that few, if any existing studies have adequately reproduced natural combinations of exposure to UV-B radiation and drought as well as their relative timing, and therefore results from these studies need to be carefully evaluated for their relevance (see **Fig. 4**).

Reduced cloudiness is expected to lead to increases in UV-B radiation and future seasonal droughts in Mediterranean ecosystems.^{21, 280} A study where solar UV radiation was filtered in a Mediterranean ecosystem under normal and reduced rainfall, showed plants to be tolerant of UV-B radiation independently of the rainfall regime and seasonal climatic conditions. In this case, the species tested were evergreen Mediterranean shrubs with tough thick leaves high in phenolics.³²¹ Thus, life history, together with exposure protocols, choice of species, and dose-dependency will all determine the outcome of the interactive effects of drought and UV-B radiation.

Perhaps the most important complication in attempting to understand the interactive effects of drought and UV-B radiation, is that both variables alone induce complex responses, and any simultaneous exposure to both variables will result in an amplification of that complexity. Cross-protection is multifaceted and likely to involve decreases in leaf area and possibly stomatal gas exchange, increases in leaf and cuticle thickness, as well as enhanced concentrations of antioxidants, flavonoids and potentially a range of other secondary metabolites such as proline and volatile terpenes.⁷ Osmotic stress-induced upregulation of the UVR8 transcript and protein levels might also contribute to interactive effects of drought and UV-B radiation.¹⁰⁵ This complexity can also be observed in a study where drought, in the presence of a background of UV radiation, increased canopy temperature in a grassland ecosystem, resulting in decreased accumulation of above-ground biomass.²⁴⁴ Thus, interactive effects of drought and UV-B radiation need to be considered in the context of prevailing and future conditions, particularly warming temperatures.

3.4.2 UV radiation and temperature

On balance, rising average air temperatures associated with climate change are expected to affect the growth and survival of many plant species and animals, and perturb many ecosystem processes. In addition to changes in average temperatures, extremes in temperature have increased in frequency and magnitude,²⁸⁶ which can have severe local and regional consequences. Changes in seasonal weather patterns and sky conditions are bringing periods of high temperatures, which are often accompanied by high solar radiation including UV-B radiation to many regions. However, extreme cold temperatures can also be accompanied by

high UV-B radiation, particularly at high elevations and latitudes in springtime where UV-B radiation reflected by the snowpack²⁵⁹ often supplements the irradiance received by organisms exposed to the sun.¹⁶⁸ The combinations of UV-B radiation and temperature can affect acclimation processes in plants (see below), which are important in terms of understanding the response of ecosystems to climate change, how future agroecosystems will be managed, as well as how vegetation itself affects air quality and climate (see Chapter 6).

Exposure to high UV-B radiation and elevated temperatures elicits a variety of chemical responses in plants. For example, UV-B radiation can induce production of volatile hydrocarbons, such as the isoprenes,¹⁹⁴ and this has been associated with heat tolerance mediated by membrane stabilisation. Typically, emissions of isoprene occur in woody plants, contributing to air pollution and global carbon. Global annual emissions of isoprene are estimated to be equivalent to 300 Tg carbon yr⁻¹ ($= 300 \times 10^{12}$ g C yr⁻¹) with changes depending on climate change and land-use.¹²⁷ Isoprenes, as well as other plant-produced biogenic volatile organic compounds such as monoterpenes, have an important effect on atmospheric composition, and ultimately climate. Exposure to elevated temperature combined with UV-B radiation can cause more isoprenes to be emitted than under elevated temperature alone, as was found for European aspen.²⁰³ UV-induced isoprene production is synergistically enhanced in response to higher temperatures, and this has significant implications for both plant thermotolerance and plant-herbivore interactions.¹⁰⁴

An outdoor field experiment in Finland found that supplemental UV-B radiation enhanced accumulation of condensed tannins in aspen, but this increase was negated by a temperature treatment of 2°C above ambient in the spring and summer.²⁶⁶ This process may directly impinge on herbivory, given that tannins act as defence compounds that inhibit digestion (also see section 6). In willow, the same combination of UV-B radiation and temperature produced a similar pattern of effects on the accumulation of phenolic compounds.²⁴⁵

It is well known that the total content and composition of flavonoid compounds in plant leaves can be modified by a number of environmental factors including UV radiation, and high and low temperatures.^{76, 238, 249, 260, 349} For example, kale (*Brassica oleracea* var. *sabellica*) exposed to a low temperature of 5°C accumulates almost twice as much of the polyphenol, kaempferol-3-O-sophoroside-7-O-glucoside, as plants at 15°C. Such stimulatory effects may also completely mask UV-B-induced accumulation of flavonoids, as was seen in an outdoor study where plants under low temperatures accumulated high concentrations of UV-screening pigments, and this response was unaffected by the UV-exposure regime.⁷⁶ However, the profile (or composition) of the polyphenols is also modified, whereby kale plants at 15°C accumulate *ca* 25% more kaempferol-3-O-caffeoyl-sophoroside-7-O-glucoside but 30% less kaempferol-3-O-sophoroside-7-O-glucoside.²³⁸ At present, the function of these changes in phenolic profiles are not clear, although some of the compositional changes result in compounds with higher antioxidant activity. Since flavonoids are considered desirable by the food and nutrition industries (see also sections 5.2 and 5.3), an understanding is needed of changing phenolic profiles under different environmental conditions.

4 Perception of and response to UV radiation in animals

UV-B radiation has the potential to damage tissues in animals, but many animals, like humans (Chapter 2), have mechanisms that protect against the potentially deleterious effects of UV-B radiation. Nonetheless, there are reported cases of UV-induced injury in animals (see section 4.1; and ref.⁵⁰). Apart from UV damage, many animals perceive UV radiation and can use these cues to lessen exposure to intense UV radiation. Also, some animals use UV radiation as a source of information for mate selection, foraging, predator avoidance, and

other behaviours. Traditionally, an anthropocentric or human-centric perspective has resulted in a narrow definition of “visible light,” appropriate only for human vision. However, it has long been known that many species have vision that encompasses different wavelengths of the spectrum, sometimes including the UV region. Animals known to have UV vision include species of insects, amphibians, reptiles, birds and mammals.⁸¹ While advances have been made in understanding the mechanism of UV vision in animals, it is unclear how changes in the UV environment, as a consequence of changes in stratospheric ozone and climate change, might alter the UV sensory responses of these organisms (see section 4.2).

4.1 UV radiation damage to animals

Ultraviolet-B radiation is known to be potentially deleterious to a wide variety of terrestrial animals. Under controlled conditions, it has been shown that UV-A and UV-B radiation can damage the skin and eyes of various amphibian species (e.g., newts, frogs, bullfrogs, treefrogs), with the potential to negatively affect their foraging ability and fitness (reviewed by refs^{29, 47}). For example, in South America, there are indications that land-use and climate change may lead to increased exposure to UV radiation in the habitats of frog species, e.g., *Hypsiboas curupi* and *Hypsiboas pulchellus*.^{193, 198, 254} However, while UV radiation may impair vision and cause DNA damage to frogs, it is not considered at present to be among the most important environmental factors contributing to the reduced fitness and abundance of several frog species in this region.⁶⁶

4.2 UV vision in animals and ecological implications in changing environments

The eyes of insects and mites have specific rhodopsin photoreceptors that perceive UV radiation,²²⁵ which may be important in avoiding excessive UV radiation.²²² In other insects, such as damselflies, UV-reflecting wings appear to play a direct role in mate recognition by creating visual signals of sex and age.¹²⁵

Birds have UV-A vision and photoreceptor UVS-cones (sensitive to wavelengths longer than 355 nm), which may assist in foraging and mate choice.⁸¹ For instance, woodpeckers use visual cues in the UV-A region to forage on decaying wood, which differs in UV-absorption according to the extent of its fungal colonisation. Changes in the amount of UV radiation in the environment (e.g., due to changing weather patterns or forest cover) may affect visibility of these fungi and hence alter the behaviour of woodpeckers foraging for them. Changes in mutualisms of this sort have broad consequences for ecosystem function.²⁴⁶ In other birds, UV-absorbing melanin in their feathers has been linked with sexual selection, UV-protection and thermoregulation, and UV protection over wide geographic gradients.¹¹⁸ Many species of bird display strong sexual differentiation (dichromatism), creating specific patterns through both accumulation of melanin and UV-reflectance of feathers.⁸⁷ UV patterning²³³, including UV-absorbance and reflectance, are not limited to feathers and their putative role in mate selection, but are also used in a much broader range of visual recognition processes. For example, UV-reflection of bird eggs attracts aerial predators.^{233, 354} Conversely, UV-absorbing melanin in egg shells may protect eggs from UV-B radiation directly and reduce their visibility to predators, although the dark pigmented colour may cause overheating in some environments. Across a variety of species, including a palmate newt (*Lissotriton helveticus*), the expression of SWS1 opsin, a UV-photoreceptor in the eyes of animals, is UV-dependent^{191, 214}; furthermore, plasticity in expression of the photoreceptor depends on the habitat of origin of the population. This suggests that changes in the amount of UV radiation in the environment during the development of these newts could affect visual sensitivity in the UV region.^{114, 284}

The role of UV-B radiation has been relatively well-studied in the case of lizards. Lizards kept in captivity are routinely exposed to low background levels of UV-B radiation to enhance vitamin D synthesis and their overall health.⁹⁷ UV-reflectance of lateral blue spots in male lizards has a clear role in male-male interactions, including the processes of mutual assessment.²¹³ If two males have an equal signal from their UV-reflecting throat patch, their behaviour towards each other is more aggressive.²¹²

At present, evidence for an ecological role of UV vision in animals is steadily increasing, but detailed information of the functional role of UV-absorbing or reflecting tissues often remains a matter of speculation. There is also a lack of information on the dose-response of UV-visual recognition processes. Thus, it is not known how changes in stratospheric ozone and climate change-driven alterations in exposures to UV radiation will influence visual cues in animals or whether altitudinal or latitudinal gradients in UV radiation might affect migration or range shifts in these animals. Nevertheless, understanding of UV vision in animals is of direct relevance in the context of food security and specifically plant-pest and plant-pollinator interactions.

5 Food security and agricultural ecosystems

At mid-latitudes and the tropics, there are indications of recovery of ozone in the upper stratosphere. However, the total ozone column, which is the metric of greatest relevance for terrestrial ecosystems, has not yet started to recover. Because of increasing concentrations of greenhouse gases, the total ozone column over mid-latitudes will be larger by the second half of the 21st century compared to the time prior to the release of the ozone depleting substances into the atmosphere. Changes in total ozone over the tropics will be relatively small and will depend on emission scenarios and climate change-related phenomena (Chapter 1 and ref.²⁰) Nevertheless, the relatively high levels of UV radiation that occur in the tropics and at high elevations, together with ozone-independent, location-specific factors such as decreasing concentrations of aerosols, less cloud cover, and changes in land-use (Chapter 1), mean that crops may still be subject to significant changes in exposure to UV radiation. Some areas will also receive less UV radiation where pollution levels continue to be high, including increasing frequencies of smoke from forest fires (Chapter 4). These levels of complexity can affect agroecosystems with respect to growth, development and survival. It is in this context that crop plant and agricultural responses to UV radiation and climate change will be assessed here. Particular attention is given to defence mechanisms of plants, implications of genotype, and changes in crop quality mediated through changes in their biochemistry.

5.1 Linking UV radiation and climate effects to food security

The interactive effects of UV radiation, climate change, and changes in land-use and management practices are likely to have consequences for agriculture and food security. For example, these factors can modify yield and crop quality, pest and disease resistance, and overall vulnerability or adaptation to the environmental changes (**Fig. 5**). From the human intervention perspective, clearing of land for increased agricultural production to cope with growing populations, leads not only to increased exposure of agroecosystems to UV radiation, but also to poorer quality of soils and soil erosion. In areas receiving increased UV radiation, plants may more readily express acclimative mechanisms against disease, herbivores, and other environmental stresses. Farmers and growers are also becoming increasingly interested in the advantage of UV-induced stimulation of desirable secondary metabolites, such as the polyphenolics, in order to achieve improved crop response to stress conditions, including drought, pests and diseases.^{1, 100, 142, 146, 334, 335}

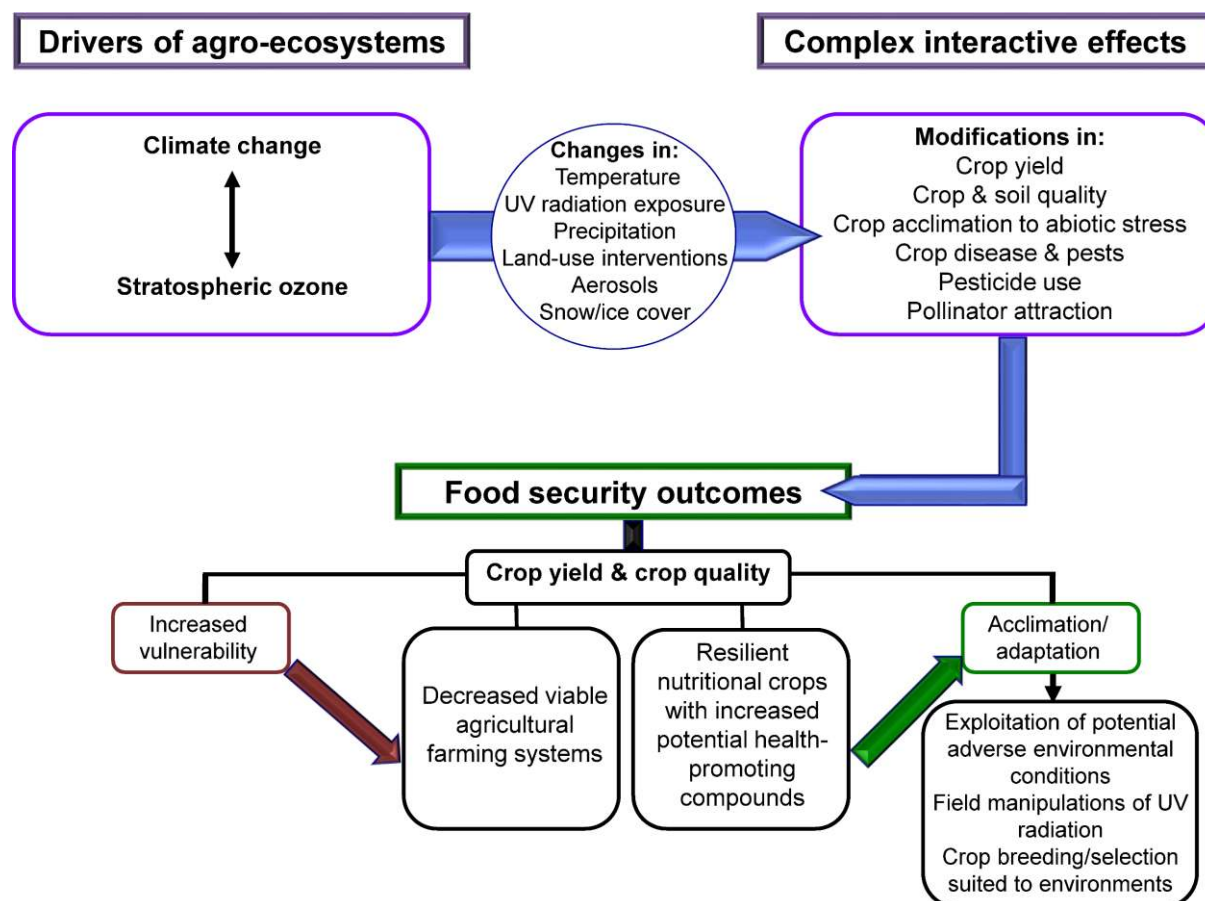


Fig. 5 Examples of current and evolving drivers of change on food security, showing the effects of linkages between changes in stratospheric ozone and climate.

5.2 Effect of genotype and environment on crop yield and quality

The degree of acclimation of plants to stress conditions is often dependent on cultivar or genotype,^{201, 314, 349} as well as location and growth conditions.^{95, 349-351} Environmental conditions and genotype have been shown to be key factors that determine plant response and yield, and are indicative of the general phenotypic plasticity of plants (changes in morphological, physiological and metabolic attributes). The roles of both the environment and genotype are especially important when assessing current and future plant acclimation to stressful environments, including locations exposed to high levels of UV-B radiation, low rainfall, and extremes of temperature (e.g., Andean Altiplano and Tibetan Plateaux). Thus, research investigating the 'environment x genotype' response of crop plants is important for selection of genotypes suitable to particular environments and levels of UV-B radiation. The composition, concentration and antioxidant activity of polyphenolics change according to exposure of plants to elevated UV-B radiation and vary strongly with plant genotype.^{250, 349} Because of the potential benefits of antioxidants (conferring free radical scavenging

capability) and other plant components, the selection of responsive genotypes or cultivars can be used to improve the nutritional status of a crop.²⁴² These benefits may include the potential for reducing the risk of health-related diseases such as cardiovascular disease and Type 2 diabetes.^{268, 316, 341}

5.3 Importance of secondary metabolites in agro-ecosystems

Ultraviolet-B radiation regulates the accumulation of numerous secondary metabolites, including flavonoids and other compounds derived from the phenylpropanoid pathway. These metabolites are important for plant growth and development, as antioxidants, UV-screening pigments, herbivore and pathogen deterrents, as well as serving as pollinator attractants and improving nutritional quality.^{310, 328} flavour, visual appeal, and desirability of many foods (see refs.^{50, 65, 163, 218, 288, 298, 302, 335} and references therein). However, exposure to UV-B radiation may cause both desirable and less desirable changes in nutritive properties. For example, UV-B radiation can decrease protein content in some crops or increase essential fatty acids not synthesised by humans and other animals (i.e., polyunsaturated linoleic and linolenic acids), while decreasing other beneficial fatty acids, such as the monounsaturated oleic acid, as was found in a study on soybean seeds.²⁶⁹

The UV-B-induced regulation of phenolic compounds can occur under low levels of UV-B radiation in many plant species, including in a range of economically important crops in which these metabolites contribute to food quality and/or value. For instance, UV-B radiation mediates increased accumulation of the potentially nutritionally-valuable flavonoid compounds, quercetin and kaempferol, in skins of grapes.¹⁹⁵ The phenolic composition of grape-skins can also change along latitudinal gradients. This was shown in a study where these flavonoid compounds were favoured in the south compared with the north (from 36.7°N Jerez, Spain to 50°N Geisenheim, Germany), a change which positively correlated with overall solar radiation across multiple European sites.⁸⁸ This finding suggests that field manipulation of the exposure of grapes to UV-B radiation and other fruit crops could be exploited to enhance desirable characteristics. Such field manipulations are already in development.^{126, 133, 255, 335}

Although UV-B radiation can affect food quality, this does not only involve phenolics, but a much broader range of metabolite classes including UV-regulated terpenoids, aromatic esters and others.²⁹⁷ In peaches exposed to UV-B radiation, levels of the flavour-related monoterpene, linalool, decrease, while concentrations of sesquiterpene (E,E)- α -farnesene increase.¹⁹⁴ Volatile isoprenes have also been associated with thermotolerance (see section 3.4). Specific glucosinolate compounds may also accumulate in plants exposed to UV-B radiation,¹³⁰ and may lead to the production of certain defence compounds against herbivory, creating another link with observations of reduced herbivory in plants exposed to UV-B radiation (see section 6.2), although the degree of resistance to herbivory under UV-B radiation may also be dependent on the type of herbivore.(see refs¹⁰⁴; and section 5.4)

Decreases in UV-B radiation in southern South America and Australasia as the stratospheric ozone layer recovers (Chapter 1), may have negative effects for plants and agricultural crops in some cases. For example, as noted above, since UV radiation generally enhances production of plant secondary metabolites that deter many plant herbivores¹⁰⁴, a decreased induction of these polyphenolics may result in increased herbivory and plant disease. It follows that from an environmental and food safety perspective, reduced cross-protection against herbivores, resulting from decreased UV-induced accumulation of phenolic compounds in crop plants under projected lower future UV-B radiation exposures, may result in increased pesticide use.²⁷ There is also evidence that UV radiation can promote the breakdown of many pesticides (e.g., fenitrothion³⁴⁰, triazophos^{180, 267}).

5.4 Potential effect of UV radiation on the visibility of crops to insect pests and pollinators

As well as being herbivores, insect pests are the main carriers of plant viruses, which are a major cause of plant disease and restrict yields through decreased plant vigour.⁹ In agricultural and horticultural environments, reductions in UV radiation, whether through climate change (e.g., cloudiness, aerosols, forest fires) or deliberate intervention (e.g., the use of UV-attenuating screens, plastic films or nets), can reduce visibility of crops for some insect pests. However, certain pests, such as whitefly, aphids, and thrips may be more damaging to crops in environments with UV radiation compared with environments where UV radiation has been attenuated or reflected,^{9, 179} although exceptions have been reported.^{26, 176} On the other hand, some beneficial insects such as pollinators, are more effective in environments containing UV radiation, allowing them to use floral cues such as UV-absorbing/reflecting nectar guides (reviewed in ref.¹⁹⁶). The floral patterns produced by nectar guides can be species-specific as found in the genus *Potentilla* where flowers of species from different regions of its distribution appear similar in the visible spectrum but differ in their UV nectar guides, presumably as an adaptation to attract different pollinators (**Fig. 6**).

These effects of UV radiation on insects have implications for crop yields and the use of agro-chemicals to control pests. However, in controlled environments, growers must balance the benefits of UV radiation for plants providing higher food quality^{178, 211} against any potential costs in terms of the visibility of the plants to pests such as fruit flies (*Drosophila suzukii*¹⁸⁰) thrips and aphids.^{1, 148}

Thus, the interplay of changing levels of UV-B radiation and increased frequency of extreme weather events is likely to add to the current and projected vulnerability

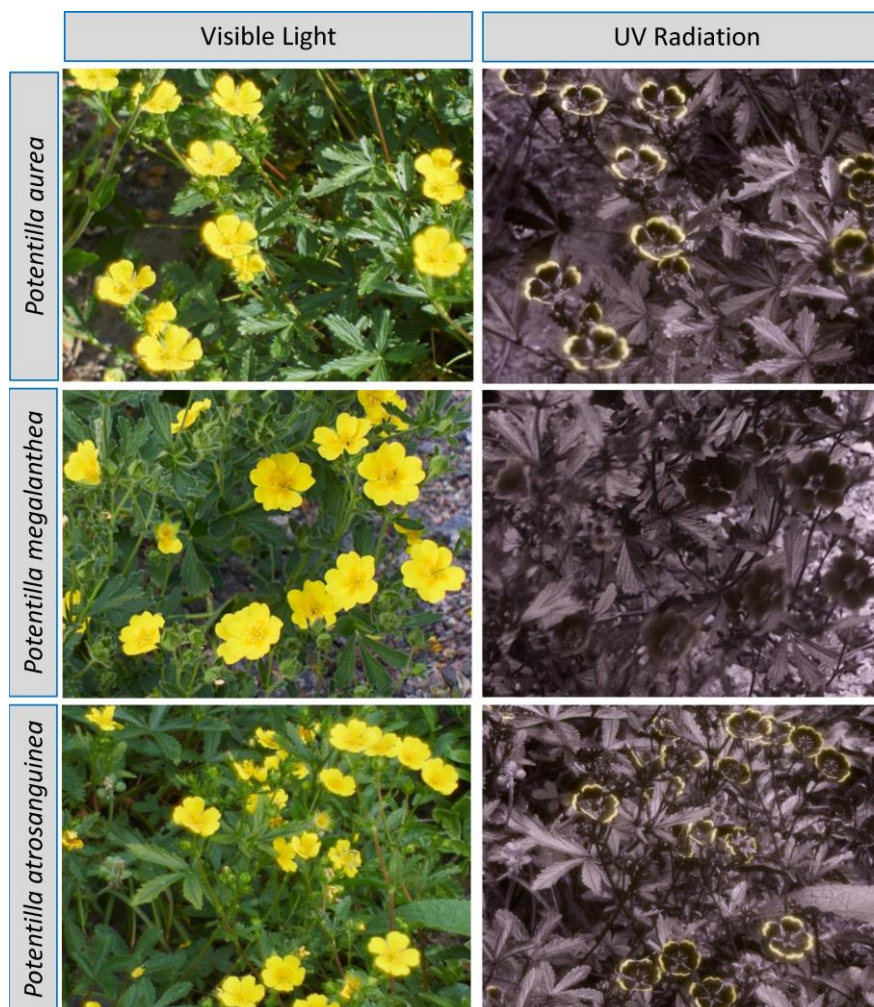


Fig. 6 The three *Potentilla* species with different origins growing together in Helsinki Finland: *Potentilla atrosanguinea* var. *argyrophylla* (Himalayan cinquefoil) originates at high elevations; *Potentilla megalanthea* is from Japan; and *Potentilla aurea* is European. While looking similar in the visible spectrum their flowers have very different UV-absorbing and reflecting nectar guides that are visible to insect pollinators. UV photographs were taken with a filter blocking visible radiation but transmitting in the UV-A as far as 325 nm. Photographs by T.M. Robson and P.J. Aphalo.

of agriculture with consequences for food security (**Fig. 5**). The key climate drivers together with UV-B radiation that modify plant development and yield are usually temperature and water availability.^{241, 289, 290} Consequently, the capacity of plant acclimative mechanisms to adjust to the rapidly changing conditions will become increasingly important.

6 Ecosystem functioning

Terrestrial ecosystems can be modified in several ways by the interactive effects of ozone depletion, UV radiation and climate change. Below, we consider recent findings that address the impacts of these interactions between plants (plant-plant), plant-herbivore, pest-pathogen, and litter decomposition. Some of these processes, particularly litter decomposition, are important in biogeochemical cycles. The consequences of alterations in these ecosystem processes for nutrient cycling and climate change are addressed more fully in Chapter 5.

6.1 Plant-plant interactions

Plants interact with one another in positive (facilitation) and negative (competition) ways and these interactions can ultimately change the composition of plant communities and their development following disturbance (succession). Competition between crops and weeds is also an important process affecting agricultural productivity and can require considerable labour and economic investment in weed control. Past studies have shown that enhanced UV-B radiation can shift the balance of competition between crop and weed species, and that these changes are linked to differential effects of UV-B radiation on plant morphology, which then alters competition for light within plant canopies (reviewed in ref.³⁷). Similarly, exposure to ambient UV-B radiation has been shown to change species composition in alpine plant communities, and these changes were also associated with differential effects of UV-B radiation on plant height and leaf area.³⁵⁵ Modelling studies confirm that these differential effects of UV-B radiation on plant growth and morphology can lead to shifts in competitive relationships among species.³⁰¹ At least some modifications to shoot morphology are likely mediated by the UV-B photoreceptor, UVR8.^{159, 271} Plants appear to use UVR8, along with other photoreceptor proteins (e.g., phytochromes), to sense changes in the light environment caused by the proximity of other plants.^{129, 220} Conditions of low light (shade) inactivate UVR8, which then results in plant resources being redirected from defence to rapid growth.²²⁰ However, while this strategy helps the plant to compete for light with its neighbours, it also makes it more vulnerable to the attack of pathogens and pests (reviewed in refs^{24, 28}; see section 6.2 below).

6.2 Herbivory and plant-pathogen interactions

Plant responses to UV-B radiation have consequences for organisms at various trophic levels or positions along the ecological food chain from producer to consumer. Solar UV-B radiation-induced reductions in herbivory have been well-documented in the field, and when this occurs, may be proportionally much larger than the effects of UV-B radiation on inhibiting plant growth (reviewed in ref.²⁶). However, there are also instances where herbivory increases with UV-B radiation (see section 5.4). Herbivorous insects can perceive solar UV-B radiation,²²¹ although many of the inhibitory effects of UV-B radiation on insect herbivory and pathogens are thought to be indirect (i.e., mediated by changes in host-plant chemistry; reviewed in ref.²⁴). More limited evidence indicates that solar UV-B radiation can reduce infection by some plant pathogens. This increased pathogen resistance was observed in experiments where plants were pretreated with different amounts of UV-B radiation before inoculation with a pathogen.⁹¹

Shade-intolerant plants often down-regulate or decrease their defences against pathogens and pests in those leaves that are exposed to shade or shade signals (such as a low red to far-red ratio, R:FR),^{68, 152, 183, 231} presumably allowing for resources to be redirected into growth responses to avoid shade. According to this interpretation, plants growing in patchy canopies use solar UV-B radiation as a “gap” signal to adaptively regulate their growth and defence phenotypes. The interplay between shade signals (such as low R:FR perceived by phytochromes) and gap signals (such as high levels of UV-B radiation) may optimise the allocation of resources between growth and defence (see ref.⁹⁰ and reviews^{24, 220}).

Some of the changes in plant chemistry elicited by natural levels of solar UV-B radiation involve compounds known to be important for plant interactions with other organisms (reviewed in refs^{104, 343}). Known defence-related compounds regulated by UV-B radiation include phenylpropanoid compounds,¹⁵³ isoflavonoids,^{98, 358} conjugated polyamines,⁹⁰ cuticular waxes,¹⁷⁷ proteinase inhibitors,^{154, 300} and jasmonates,⁹⁹ among others. These effects of solar UV-B radiation on defensive chemistry can be considered as specific, presumably mediated by specific UV-B photoreceptors. However, the role of UVR8 in mediating effects of UV-B radiation on secondary compounds has so far been demonstrated only for flavonoids and other soluble phenolic compounds.^{91, 230}

In spite of the effects of UV-B radiation on plant defence against several herbivores and certain pathogens, the connections between UV-B radiation and the key hormonal pathways that regulate plant defence (i.e., the salicylic acid (SA) and jasmonic acid (JA) pathways), require further research. Early reports of effects of UV radiation on SA and expression of marker genes for SA should be interpreted cautiously, as many of those experiments used doses or wavelengths of UV radiation not present in the terrestrial environment (such as UV-C, < 280 nm), or unbalanced UV-B radiation treatments (high UV-B radiation delivered against low PAR; see **Fig. 4**). Similar limitations apply to early studies of effects of UV radiation on JA activity (reviewed in ref.²⁴).

Some well-characterised effects of UV-B radiation on plant defence come from experiments that tested plant resistance to herbivorous insects, and necrotrophic pathogens (pathogens that kill their host cells). This has led to follow-up work focusing on interactions with JA-signalling. A few studies have shown that genetic perturbations impairing synthesis of JA can effectively cancel out some anti-herbivore effects of solar UV-B radiation, leading to the suggestion that JA-signalling is required for those effects of solar UV-B radiation that increase plant resistance to herbivory.^{64, 90, 263} However, UV-B radiation can also affect plant defence against herbivores and pathogens via mechanisms that are not mediated by JA.⁹¹ The positive effects of UV-B radiation on JA-signalling have been attributed to increased biosynthesis of JA⁹⁹ or sensitivity,⁹⁰ but the molecular mechanisms linking perception of UV-B radiation and JA- signalling remain to be elucidated.

6.3 Decomposition of litter

The decomposition of dead plant material (i.e., litter) drives the rate at which nutrients are recycled and is a strong determinant of carbon storage and soil fertility in terrestrial ecosystems. In general, the overall rate of decomposition is dependent on the temperature and moisture availability, which affects the activity of decomposing micro-organisms (bacteria and fungi), as well as the type of plant litter inputs (e.g., leaf vs woody tissue; evergreen vs deciduous leaves). Substantial evidence now indicates that solar radiation (UV and short wavelength visible radiation) can also drive litter decomposition via several mechanisms, with the net effect of these processes either accelerating or retarding decomposition, depending on quality of the litter and environmental conditions. Climate change will likely

alter the importance of UV radiation in decomposition and in regulating cycling of carbon in a number of terrestrial ecosystems.

Solar radiation in the UV and short-wavelength visible regions (blue and green light) can directly break down the biochemical components of plant tissue, including relatively stable compounds, such as lignin, which absorb UV radiation, through a process called photochemical mineralisation (**Fig. 7**; refs^{25, 38, 166}). These light-driven modifications in litter chemistry can, in turn, increase the ease with which microbes can decompose litter.^{17, 22} This latter process is often called photo-facilitation or photopriming (see Chapter 5). However, solar UV radiation, especially shorter wavelength UV-B radiation, may also inhibit the activity of microbes and change the composition of the microbial community, which then works in opposition to photo-facilitation.^{38, 190} The net effect of these mechanisms is modified by environmental conditions (e.g., availability of moisture) and the spectral quality of sunlight, which varies depending on stratospheric ozone depletion, cloud cover, pollution,

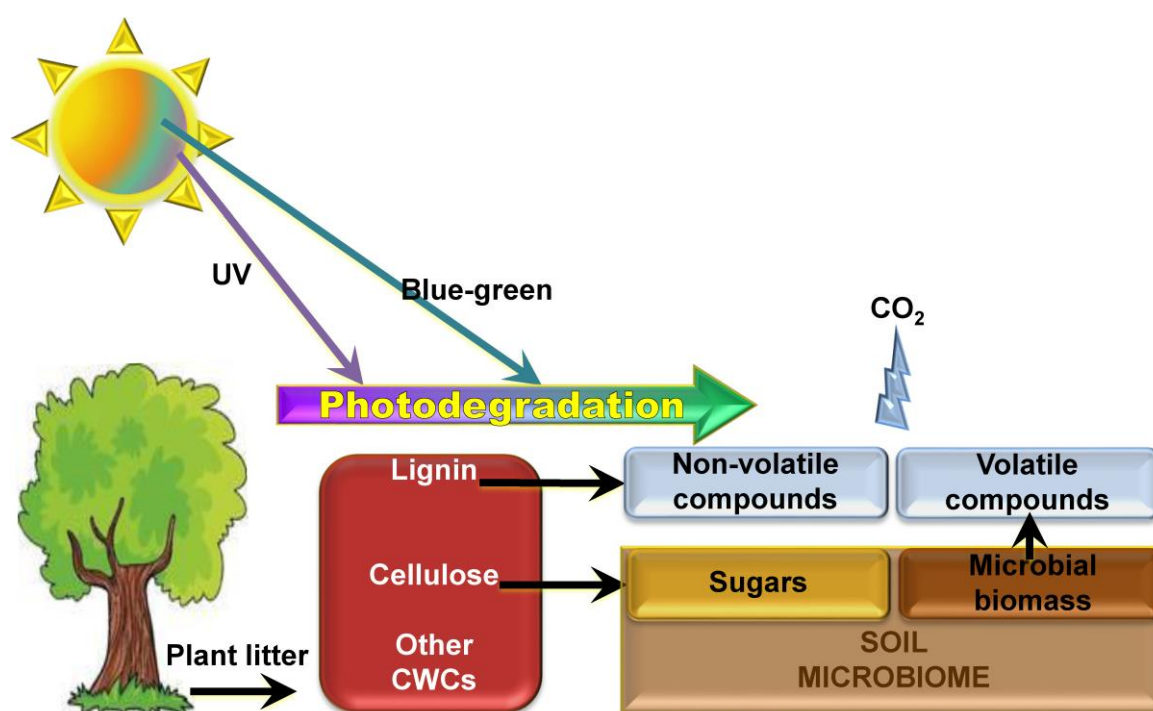


Fig. 7 Conceptual model of the effects of solar radiation on litter degradation and microbial decomposition in terrestrial ecosystems. UV radiation and blue-green light cause the direct breakdown of lignin, cellulose and other plant cell wall components (CWCs), forming non-volatile and volatile compounds, such as carbon dioxide (CO₂), the latter being released to the atmosphere. This abiotic process is often referred to as photomineralisation. The changes in litter substrate resulting from photodegradation enhance the microbial breakdown of litter through a process called photo-facilitation. UV photons in sunlight may also directly inhibit the activity of decomposing microbes. Figure adapted from ref.²⁵.

and plant canopy.

Recent studies have shown that photodegradation (photochemical mineralisation plus photo-facilitation) occurs in a variety of environments,¹⁷ but the mechanisms and quantitative importance of this process in driving the overall decomposition of litter remains unclear in many cases. Since UV radiation can also inhibit microbial activity, a shift in spectral composition (i.e., UV-B:PAR ratios) would likely change the balance between photo-facilitation and microbial inhibition. This may be one reason why some experimental and modelling studies fail to detect a relationship between photodegradation and lignin content of

litter.^{3, 190} Long-term studies indicate that increased rates of decomposition due to photodegradation become evident only in later stages of decomposition, as was found after four months for savanna litter in a controlled experiment,¹⁸⁹ and after 12 months in a semi-arid ecosystem.³³¹ This suggests that the availability of substrates to microbes is only noticeably increased by photo-facilitation once readily-available substrates in fresh litter have been depleted. A diel time period (i.e., 24 h) appears to allow microbes to benefit from daytime photo-facilitation, possibly recovering during darkness, as well as utilising the extra humidity at night.^{120, 189}

Field studies continue to show that photodegradation contributes most to the acceleration of litter decomposition in hyper-arid (annual precipitation < 150 mm), arid, and semi-arid ecosystems.^{145, 330} In two contrasting locations on the Mediterranean steppe, UV radiation increased the decomposition rate of grass and shrub litter in a continental climate, but not in a high rainfall maritime climate.^{6, 120} These findings suggest that, in drylands, photochemical mineralisation dominates under the driest conditions, whereas photo-facilitation tends to dominate under slightly moister conditions. The acceleration of decomposition attributable to photo-facilitation can even be detected in sub-tropical and temperate environments in both litter and coarse woody debris.³⁴⁸ However, when moisture levels are favourable enough to support high microbial activity, UV radiation can have negative effects on decomposition, presumably because of direct inhibitory effects of solar radiation on the microbial populations.²⁵²

The majority of field photodegradation studies to date have been conducted in ecosystems occurring in dry (arid and semi-arid) rather than moist (mesic) climates.³⁸ However, the interaction of moisture and photodegradation has recently been garnering attention.^{120, 293, 330} In moist, forested ecosystems, the amount of solar radiation reaching litter through the canopy can alter decomposition rates.²⁰² Different types and densities of canopy affect both the amount of radiation reaching ground level and its spectral composition.¹¹² This implies that shifts in type of vegetation occurring because of changes in land-use and climate are likely to affect decomposition rates through photodegradation interacting with concomitant changes in temperature and moisture.^{12, 55, 262} Typically, the encroachment of woody plants leading to conversion of grasslands to shrublands driven by climate change and/or land abandonment, will alter litter composition and chemistry. This will shift C:N ratios in litter, affecting not only microbial activity but also photo-facilitation of litter and direct photodegradation.^{12, 52, 137} In addition to shifts in type of vegetation, the exposure of litter to solar radiation will be determined by plant morphology and functional strategy. In habitats where standing dead litter remains on the plant, this will present a greater surface area exposed to sunlight than situations where litter falls to the ground becoming easily mixed with soil which then reduces photodegradation.^{39, 136, 251, 330, 331}

The structure and biochemical composition of litter produced by different plant forms plays a significant role in determining the underlying rate of decomposition. Hence litter with high lignin content may decompose slowly and be most affected by direct photochemical degradation.^{16, 103} However, variations in photodegradation among species independently of their lignin content,¹⁶⁶ suggest that other traits of litter are also important (see ref.²⁰ for additional discussion). The UV radiation received by plants during growth can affect leaf morphology and the amount and composition of phenolic compounds that accumulate in the leaf epidermis,⁵⁰ as well as affecting the rate at which leaves will break down. These traits may continue to modify the optical properties of the leaf and hence the extent to which solar radiation penetrates the leaf during the early stages of decomposition.⁸⁵ Likewise, the depth and density of litter, its physical movement (e.g., by wind, rain), and the degree to which

litter mixes with soil will determine the surface area exposed to sunlight, factors that are likely to be highly important for photodegradation.^{38, 166}

The insight that recent research brings into the role of UV radiation and short-wavelength visible light in photodegradation in humid temperate as well as arid biomes,^{5, 70} means that photodegradation has the potential to modify processes such as carbon cycling across many biomes. This broader relevance compared with our past knowledge of photodegradation extends its scope to affect the biogeochemistry of terrestrial ecosystems under climate change and with future stratospheric ozone recovery (Chapter 5).

7 Climate change is altering the exposure of organisms to UV radiation

Previous assessments have focused on the effects of ozone-driven changes in UV-B radiation.⁵⁰ However, climate change is increasingly exerting a stronger control on UV-B and UV-A radiation received by organisms as a result of changing cloud cover, vegetative cover, shifting of geographic ranges of species, changing of seasonal timing of growth and reproduction, and migration. Some of the potential implications of these climate-driven changes in exposure to UV radiation for terrestrial organisms and ecosystems are addressed below.

7.1 Species migration, UV radiation, and climate change

Plants and animals are shifting their ranges to higher latitudes and elevations in response to climate change and additional changes in distributions are expected to occur in the future.^{83, 149, 257} However, species vary in their potential rates of migration. For plants, short-lived, herbaceous species (grasses and forbs) generally shift geographic ranges more rapidly than long-lived, woody species (trees and shrubs).¹⁴⁹ Non-native (i.e., introduced) species of plants also appear to exhibit higher migration potentials than native (i.e., indigenous) species.^{83, 347} These climate change-driven shifts in geographic ranges will likely alter the exposure of plants to UV-B radiation, since UV-B irradiances generally increase with increasing elevation and decrease with increasing latitude^{21, 48, 62}. However, these changes in plant exposure to UV-B radiation will not occur in isolation of other environmental factors, since a number of abiotic (e.g., temperature and moisture) and biotic (e.g., associated pests, pathogens, and competitors) factors change with the migration of organisms to higher latitude and elevation.^{149, 169} Consequently, these shifts in geographical range will likely expose organisms to unique combinations of UV radiation and co-occurring environmental factors. To what extent UV radiation plays a role in influencing migration patterns and how plants and animals respond to different conditions of UV radiation in the context of these other environmental changes as they migrate, has received little attention to date (but see section 3). However, certain insights into these effects can be gleaned from studies comparing plant populations or ecotypes whose distribution naturally spans a range of latitudes or elevations.

Plants that are adapted to grow in high elevation environments (i.e., alpine) often accumulate more UV-screening compounds (e.g., flavonoids) and have other UV-protective mechanisms compared with those plants occurring at lower elevations.^{117, 227, 304, 333, 360} These differences are likely the result of the combined effects of elevational changes in UV radiation, temperature and other factors.⁴ As discussed in section 3.4, low temperatures induce the production and accumulation of flavonoids. This may then increase levels of UV-screening and protection against oxidative stress.^{167, 182, 337} High- and low-elevation plant populations may also differ their abilities to acclimate to changes in UV radiation.³³² In wild potatoes (*Solanum kurtzianum*), populations grown at low elevation have relatively low constitutive (base-line) levels of leaf flavonoids but a high capacity for induction of flavonoids when UV radiation

increases. In contrast, plants at high elevations have high constitutive flavonoid levels, but do not necessarily increase their UV-screening in response to supplemental UV-B radiation in experimental studies.¹⁴⁷ Differential sensitivity to UV radiation of high vs low-elevation populations may also be due, in part, to population differences in DNA damage and repair, as has been shown for *Arabidopsis*.³³²

Whether there are differences in tolerance to UV radiation between native vs introduced species is unclear at present. For example, introduced populations of Chinese tallow tree (*Triadaca sebifera*), taken from south-eastern USA where the species was introduced in the 1700s, were shown to be more sensitive to UV-B radiation than native Chinese populations.³²⁹ By comparison, no differences were found in the sensitivity of seed germination to UV-B radiation in native vs introduced populations of *Verbascum* and *Echium* in New Zealand.¹³⁹ Similarly, native and non-native species showed similar levels of UV-screening when growing in a high UV, tropical alpine location.³⁶ However, UV-screening increased with increasing elevation and UV-B radiation in a non-native species (*Verbascum thapsus* (mullein)) but did not vary with elevation in the native *Vaccinium reticulatum* (ohelo). In contrast, similar levels of phenotypic plasticity (acclimation potential) between native (German) and non-native (New Zealand) populations of *Hieracium pilosella* with respect to morphological and growth response to UV-B radiation under growth chamber conditions have been found.⁴⁰ Thus, while it is generally assumed that non-native species can acclimate more readily to environmental change than native species,⁸⁴ it is unclear whether this generalisation applies to tolerance to UV-B radiation. Plants expanding their distribution into higher latitudes, would be expected to experience less exposure to UV-B radiation. As already noted, this may then lead to a decline in UV-screening compounds, antioxidants and other metabolites involved in photo-protection.⁶⁷

To date, relatively little research has exploited remote sensing to make quantitative assessments of plant responses to elevation and climate change. However, the potential to use this approach is apparent from remote sensing images of a 1-hectare area (from the Carnegie Airborne Observatory-2), using a high-fidelity visible-to-shortwave infrared (VSWIR) imaging spectrometer and dual laser waveform (LiDAR), which was calibrated against spectrophotometric measurements of leaf extracts.¹⁴ This allowed a trend to be identified for increased phenolics with elevation (excluding the upper-most measurement point) using LiDAR images at the landscape scale in the Peruvian Andean rainforest. As this approach becomes more widely adopted, it will enable the resolution of large-scale relationships with topography and climate, allowing patterns in response to UV radiation and climate change to be mapped using remote sensing of large areas. Unmanned aerial vehicles (drones) are also increasingly being used to bridge the gap between satellites and ground measurements and to measure spectral reflectance at high resolution and under clouds.²⁰⁴

Ecosystems, and populations of plant species, including native species, have responded over the eons to changing environmental conditions. However, the recent rapid rate of climate change, in particular increasing temperatures and more frequent extreme weather events, are of concern in terms of the conservation of species and habitats.²⁵⁷ Understanding the role of UV radiation in shifting distribution patterns and how readily plant populations can adjust physiologically and genetically to new UV radiation environments is therefore relevant to the conservation of biodiversity and the services that these natural ecosystems provide to humans.

7.2 Clouds, canopies, and plant response to fluctuating UV radiation

Climate change is altering cloud cover with some regions experiencing increased and other regions decreased cloud cover (Chapter 1 and ref.¹⁴⁹). The effect of clouds on UV radiation also depends on the type of clouds²⁰⁰ as well as their position relative to the sun.¹⁰⁶ These changes in cloud cover alter the long-term (days to weeks) exposure of plants to UV radiation and they can also change the short-term (seconds to hours) dynamics of UV radiation received by plants. (**Fig. 8**; ref.¹⁰⁶) Whereas considerable attention has been given to understanding plant responses to changes in average UV radiation conditions that occur over long time periods (see section 3.3, refs.^{46, 50} and references therein), far less is known about plant response to rapid fluctuations in solar UV radiation. A number of studies have, however, demonstrated that concentrations of UV-screening compounds in mature leaves can vary over the growing season²³⁷, from one day to the next,³⁰³ over the course of an individual day,³³ and in response to rapid changes in clouds.³⁶ The changes in UV-screening that occur over the day are rapid (within minutes), reversible, and have been shown to be linked to changes in the content and composition of UV-absorbing compounds (flavonoids and related phenolics).³⁶ At present, the underlying mechanisms responsible for these rapid changes in UV-radiation protection are unclear, as is the significance of these changes for plant growth and function. These findings do; however, indicate that many, but not all, plant species can rapidly adjust their UV-screening in response to fluctuations in UV irradiances.³⁴

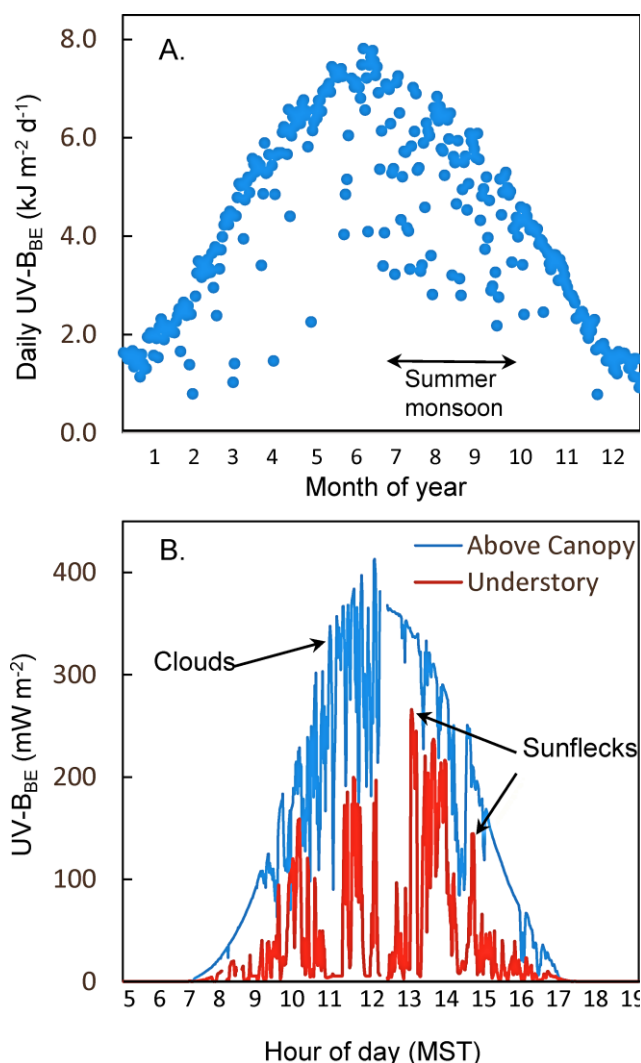


Fig. 8 Variability in ground-level UV-B radiation over multiple time scales in the Sonoran Desert, USA. Panel A shows incident daily plant effective UV-B radiation over one year (January-December; months 1-12) with the annual summer monsoon (rainy and cloudy weather) indicated. Panel B shows instantaneous plant effective UV-B radiation over a single summer day measured above (blue line) and beneath (red line) a velvet mesquite (*Prosopis velutina*) canopy. Fluctuations in UV-B radiation in the understory result from changing cloud cover and the penetration of direct solar radiation through gaps in the canopy (sunflecks). Unpublished data from P. Barnes.

The disruption of plant canopy structure (e.g., due to fire or drought-induced mortality of trees) alters the amount and spectral composition of sunlight penetrating canopies (i.e., ratios of UV-B:UV-A:PAR), but the specific changes depend on the type of canopy and vertical position (e.g., crown vs understory).²³ Recent studies using array spectrometers have captured rapid changes in the sun-shade environment under canopies by recording multiple spec-

tra every second.¹²⁸ These measurements at high temporal resolution have confirmed findings from earlier studies^{59, 112, 122} that the spectral composition as well as total irradiance differs between sun flecks and understorey shade in forests and crop canopies. The importance of this fine-scale temporal and spatial variation in UV radiation in understorey environments for plant growth and development is not entirely clear at present (but see refs^{173, 174}). There is evidence, however, that plants use the total irradiance received or modulated as cues,¹⁹² which can prime them for seasonal or periodic changes. This may therefore be an important aspect of UV acclimation in understorey species that could lead to better adjustment to conditions of variable UV radiation resulting from modified overstorey canopies brought about by climate change.

Light tends to penetrate canopies more effectively under overcast or hazy sky conditions when the ratio of diffuse to direct radiation is higher, than under clear sky conditions.^{71, 92, 184} Thus, cloudy conditions produce short-term increases in photosynthesis at the whole canopy level.^{228, 317, 318} However, because leaves that develop in the sun are more efficient in using direct than diffuse radiation, and efficiency of leaves that develop in the shade does not differ significantly under changing sky conditions⁵⁷, caution must be exercised in generalising from these results. Conclusions that plant productivity will be enhanced by projected increases in diffuse solar radiation resulting from manipulating aerosol levels in the atmosphere to reduce climate change (i.e., geoengineering, see Chapter 1) must be viewed with a high degree of uncertainty because they will depend on the geographic location, on the extent of the reduction in incident irradiance, and whether the increased canopy light-use efficiency from diffuse radiation is sufficient to offset this and persist in the long term.³⁴⁶

Remote sensing of vegetation using satellites is routinely used to measure primary productivity and leaf pigments involved in photosynthesis; this technique has been used extensively for the scaling of ecosystem processes related to the carbon cycle.³⁵³ Most of these ecosystem process models have been developed for use in combining leaf-level and remotely-sensed data, but new possibilities to better understand canopy reflectance of UV radiation are being made possible by the capacity to extend these remotely captured images and spectral data into the UV range of the spectrum.

Radiative transfer models used to model canopy optical properties and determine the fate of solar radiation have not yet been extended into the UV range, e.g., the discrete anisotropic radiative transfer model (DART¹¹⁹). These models can incorporate sub-models for leaf optical properties (e.g., PROSPECT-D¹⁰⁷ and Fluspect-CX³²³), which previously have been applied for optical estimation of chlorophyll and carotenoids but if extended into the blue light and UV-A regions could include estimation of anthocyanins³²⁴ and flavonoids. This may be facilitated by the new generation of those satellites designed for monitoring vegetation, which include the capacity to detect wavelengths spanning into the UV portion of the spectrum (from the European Space Agency, 270-370 nm for Sentinel-5 Satellite and Sentinel-5-precursor satellite). An alternative approach is to extend atmospheric radiative transfer models, such as libRadtran (Chapter 1 and ref.¹⁰¹) and the tropospheric and visible solar UV radiation model (http://cprm.acom.ucar.edu/Models/TUV/Interactive_TUV/), to include radiative transfer through plant canopies or even greenhouse structures in the same way that DART and other radiative transfer models (RTMs) are being applied for the visible spectrum, or even coupling these two model types together. At the leaf level, commercial sensors (e.g., Ocean Optics Jaz¹²³) and custom-made devices (e.g.,²⁷²) have the capacity to measure leaf reflectance in the UV range in both broadleaved and needle-leaved plants.

In crop canopies, planting distance and crop species, or even the cultivar or variety planted, will dictate the canopy architecture and affect the spectral composition and total irradiance

reaching the lower leaves. These decisions also have implications for how UV-B radiation affects plant growth and defence at the canopy level in agricultural crops (see ref.²⁴ and section 5.3). With a better understanding of the mechanisms by which plants in canopies respond to UV radiation as a part of the incident spectral irradiance over vertical profiles, we can make better-informed management decisions on species and cultivar selection for specific locations.

7.3 Phenology and UV radiation

The implications of warmer winters for the seasonal timing of development or phenology have been extensively studied, with findings consistently showing both the early emergence of animals^{77, 307} and the earlier onset of plant growth.^{74, 170} Although the molecular mechanisms controlling phenology are not fully understood³⁰⁵, it is known that organisms often use a variety of environmental cues to safeguard against mis-timing of development.^{175, 282, 362} Differences among life forms in their rate of response to temperature, which is usually the predominant cue, create the potential for a disruption of ecosystem processes through a mismatch in the timing of phenology among co-existing organisms such as plants and pollinators.^{243, 264} It is likely that warmer temperatures will bring overwintering trees out of dormancy prematurely. This will produce an earlier spring bud-burst, possibly so early in the year that at high latitudes new leaves receive insufficient sunlight (and by definition less UV-B radiation) to develop as they normally would do later in the year.^{45, 232} This forward displacement of phenology due to warming may also heighten the role of alternative phenological cues (e.g., daylength and spectral quality).^{56, 339} In particular, more research is required to better understand interactions between daylength (photoperiod) and cues related to spectral quality (i.e., changes in UV-B, UV-A, blue and red light), both of which are detected by plant photoreceptors. Alterations in the timing of spring phenology, particularly at high latitudes, may expose understorey plants to new light environments in early spring when freezing temperatures may limit their physiological acclimation capacity.

8 Tracking changes in past UV radiation over geological timescales using the biochemical signatures of plants

The long-term ecological effects of UV-B radiation over geological timescales are studied by palaeoecologists interested in retrospectively reconstructing solar UV-B radiation. Identifying a reliable proxy for tracking changes in UV-B radiation based on the biochemistry of pollen and spores, would help interpretation of the effects of UV-B radiation on terrestrial ecosystems. However, even then an additional calibration would be required to separate changes in total solar radiation from those of UV-B radiation, and it would be difficult to distinguish whether these changes resulted mainly from stratospheric ozone depletion or other environmental or astronomical factors. Improvements in analytical techniques have reduced the uncertainty associated with reconstructions of solar radiation based on the biochemistry of pollen from ice cores and lake sediments that track changes in past UV radiation over geological time scales.^{115, 224} These reconstructions may provide a better understanding of the evolution of the stratospheric ozone layer and its interaction with climate change.^{158, 278} However, the extent to which UV-absorbing compounds in pollen can be considered reliable indicators of the past UV-B radiation and reflect changes at high temporal resolutions, depends upon the causative temporally-stable relationship between the accumulation of these compounds in pollen and exposure to solar UV-B radiation being experimentally verified.³⁰⁸

The preserved outer walls of fossilised spores and pollen grains are made from sporopollenin, which is highly resistant to degradation over geological time scales and contains the phenolic

compounds, para-coumaric acid and ferulic acid. Experiments using supplemental UV-B radiation have found the concentrations of these compounds to be proportional to the incident solar UV-B radiation received by the pollen.^{89, 278} Exploiting this relationship has enabled the reconstruction of UV irradiance at Lake Bosumtwi, in modern-day Ghana.¹⁵⁸ This work has shown that over a 140-thousand-year period, fluctuations in the concentration of phenolics from grass pollen contained in sediments corresponded with patterns of solar UV irradiance derived from changes in the Earth's orbit over cycles of 19-21 thousand years.¹⁵⁸ The correlation between reconstructed UV-irradiance and phenolic concentration is also evident from pine pollen³⁴⁴ and spores of the ubiquitous clubmoss *Lycopodium*¹⁹⁷ over broad latitudinal gradients, although this correlation is more robust across local elevational gradients.³⁰⁸ This is because seasonal and environmental variability and differences in UV-B radiation related to weather patterns (temperature and cloudiness) and canopy shade can confound the relationship.

The lack of standardisation and inter-comparability of samples and sampling techniques is one impediment to the wider use of the above techniques. Improvements in the two analytical approaches used to detect phenolic compounds, i.e., Fourier-Transform (FT) high-throughput infra-red spectroscopy and thermally-assisted hydrolysis methylation (THM) with pyrolysis–gas chromatography mass spectrometry (THM–GC/MS), should allow researchers to obtain more detailed information from pollen samples.^{18, 157, 285} In the latter case, precision should also be improved by calibration of changes in phenolic compounds against a known concentration of a compound added to the sample as a standard or against another compound within the pollen that does not respond to changes in solar radiation.²⁸⁵ When used in conjunction with radiative transfer modelling,³⁰⁹ these approaches show promise in distinguishing past environmental gradients in UV radiation, such as that at the end of the Permian period (*ca* 250 million years ago),^{49, 327} from other climate changes across geographical gradients, and long time-scales. This has the potential to improve our knowledge of the causes and consequences of stratospheric ozone depletion.

9 Key gaps in knowledge

Current gaps in our knowledge of the linkages between stratospheric ozone, UV radiation and climate change and their implications for terrestrial ecosystems are a direct consequence of the complexity of systems characterised by interactive loops that link climatology, meteorology and biology (**Fig. 1**). The challenge lies in developing integrated approaches to assess the effects of UV radiation against a complex background of rapidly evolving environmental conditions and increasing human interventions. The way in which ecosystems respond to the often-interactive effects UV radiation and other climate change dynamics can have important consequences for the functionality and/or productivity of agricultural and natural ecosystems, but currently leave many unknowns. This emphasises the importance of studying combinations of those environmental factors that often change with UV radiation and which may modify the response of organisms to UV radiation in terms of acclimation and productive growth. Thus far, most research has concentrated on potential interactive effects of UV radiation with temperature and/or drought. Since climate warming continues to increase, a better understanding is needed of the effects of UV-B radiation and rising carbon dioxide together with other climate variables on natural and agricultural systems. This will then facilitate assessments of future outcomes for ecosystem functioning, conservation of species, and selection of environmentally suitable agricultural crops. While growth chamber studies can make valuable contributions to understanding some of the fundamental mechanisms of plant response to UV radiation, there is still a strong need for many growth chamber

studies to be validated in the field for a realistic perspective of how organisms will respond in a more natural environment.

The balance between negative and beneficial effects on organisms will determine the current and future adaptation and sustainability of terrestrial ecosystems. Changing exposure to UV radiation and climate change factors will affect plant resistance to pests and diseases, food quality and nutritional quality, as well as potentially modifying the behaviour of terrestrial animals. These changes may also affect visual cues contributed by UV radiation for certain animals. However, more information is required to evaluate the possible implications in the context of animal response to future environments and in plant-pest and plant-pollinator interactions, which will have a bearing on food security.

While qualitative analysis of responses to UV radiation and other variables is usually possible, quantitative analyses are often lacking due, in part, to the complexity of diverse and constantly changing biological systems. For example, it is difficult to quantify the importance of processes such as photodegradation and microbial breakdown of terrestrial plant litter for soil carbon storage and emissions at regional and global scales, and their potential contribution to global warming and nutrient cycling.

Climate change together with changes in land-use will very likely continue to have strong impacts on the exposure to UV radiation of ecosystems and terrestrial organisms, including human populations. On a global scale, there is currently insufficient information on the relative contribution and implications of stratospheric ozone depletion to climate change in the southern hemisphere, and how much can be attributed to natural variability. These interactive effects need to be evaluated for the way in which they may continue to modify ecosystem response in a future with a recovering stratospheric ozone layer. In addition, emerging findings from monitoring of stratospheric ozone need to be taken into account for evaluating the possible implications of any sudden change towards the projected path of ozone recovery. This was recently illustrated in a report²²⁹ suggesting that there are unexpected indications that emissions of the banned ozone-depleting compound, chlorofluorocarbon-11 (CFC-11), have increased. The magnitude and future significance of the responses of terrestrial ecosystems to increasing or decreasing UV radiation, either dependent or independent of stratospheric ozone depletion, and in the context of climate change, remain largely unknown.

Acknowledgments

Support by the U.S. Global Change Research Program and the J.H. Mullahy Endowment for Environmental Biology is gratefully acknowledged for Paul Barnes. Sharon Robinson received funding from the Australian Research Council (DP180100113) and the University of Wollongong's Global Challenges Program. Carlos Ballaré acknowledges financial support from Agencia Nacional de Promoción Científica y Tecnológica and the University of Buenos Aires. Marcel Jansen acknowledges financial support by Science Foundation Ireland (16/IA/4418). Matthew Robson was supported by the Academy of Finland (decision number 304519). We thank Andrew Netherwood for his assistance with drafting and improving Fig. 1.

References

- 1 Abd El-Aal HA, Rizk AM and Mousa IE, 2018, Evaluation of new greenhouse covers with modified light regime to control cotton aphid and cucumber (*Cucumis sativus* L.) productivity, *Crop. Prot.*, **107**, 64-70.

- 2 Abram NJ, Mulvaney R, Vimeux F, Phipps SJ, Turner J and England MH, 2014, Evolution of the Southern Annular Mode during the past millennium, *Nat. Clim. Change*, **4**, 564-569.
- 3 Adair EC, Parton WJ, King JY, Brandt LA and Lin Y, 2017, Accounting for photodegradation dramatically improves prediction of carbon losses in dryland systems, *Ecosphere*, **8**, e01892.
- 4 Albert A, Sareedenchai V, Heller W, Seidlitz HK and Zidorn C, 2009, Temperature is the key to altitudinal variation of phenolics in *Arnica montana* L. cv. ARBO, *Oecologia*, **160**, 1-8.
- 5 Almagro M, Maestre FT, Martínez-López J, Valencia E and Rey A, 2015, Climate change may reduce litter decomposition while enhancing the contribution of photodegradation in dry perennial Mediterranean grasslands, *Soil Biol. Biochem.*, **90**, 214-223.
- 6 Almagro M, Martínez-López J, Maestre FT and Rey A, 2017, The contribution of photodegradation to litter decomposition in semiarid Mediterranean grasslands depends on its interaction with local humidity conditions, litter quality and position, *Ecosystems*, **20**, 527-542.
- 7 Alonso R, Berli FJ, Bottini R and Piccoli P, 2015, Acclimation mechanisms elicited by sprayed abscisic acid, solar UV-B and water deficit in leaf tissues of field-grown grapevines, *Plant Physiol. Biochem.*, **91**, 56-60.
- 8 Amesbury MJ, Roland TP, Royles J, Hodgson DA, Convey P, Griffiths H and Charman DJ, 2017, Widespread biological response to rapid warming on the Antarctic peninsula, *Curr. Biol.*, **27**, 1616-1622.e2.
- 9 Antignus Y, 2014, Management of air-borne viruses by "optical barriers" in protected agriculture and open-field crops, *Adv. Virus Res.*, **90**, 1-33.
- 10 Aphalo PJ, Albert A, Björn LO, McLeod A, Robson TM and Rosenqvist E, 2012, Beyond the visible: A handbook of best practice in plant UV photobiology, in *COST Action FA0906 UV4growth*, University of Helsinki, Department of Biosciences, Division of Plant Biology Helsinki, Finland <http://hdl.handle.net/10138/37558>, p. 176.
- 11 Aphalo PJ, Jansen MAK, McLeod AR and Urban O, 2015, Ultraviolet radiation research: From the field to the laboratory and back, *Plant Cell Environ.*, **38**, 853-855.
- 12 Araujo PI and Austin AT, 2015, A shady business: pine afforestation alters the primary controls on litter decomposition along a precipitation gradient in Patagonia, Argentina, *J. Ecol.*, **103**, 1408-1420.
- 13 Arblaster J, Gillett N, Calvo N, Forster P, Polvani L, Son S, Waugh D and Young P, 2014, Stratospheric ozone changes and climate, Chapter 4 in Scientific Assessment of Ozone Depletion: 2014, Global Ozone Research and Monitoring Project–Report No. 55, *World Meteorological Organization, Geneva, Switzerland*.
- 14 Asner GP, Martin RE, Anderson CB, Kryston K, Vaughn N, Knapp DE, Bentley LP, Shenkin A, Salinas N, Sinca F, Tupayachi R, Quispe HK, Montoya PM, Ccori ÁF, Delis, Díaz S, Enquist BJ and Malhi Y, 2017, Scale dependence of canopy trait

- distributions along a tropical forest elevation gradient, *New. Phytol.*, **214**, 973-988.
- 15 Atkinson NJ and Urwin PE, 2012, The interaction of plant biotic and abiotic stresses: from genes to the field, *J. Exp. Bot.*, **63**, 3523-3543.
 - 16 Austin AT and Ballaré CL, 2010, Dual role of lignin in plant litter decomposition in terrestrial ecosystems, *Proc. Nat. Acad. Sci. USA.*, **107**, 4618-4622.
 - 17 Austin AT, Méndez MS and Ballaré CL, 2016, Photodegradation alleviates the lignin bottleneck for carbon turnover in terrestrial ecosystems, *Proc. Nat. Acad. Sci. USA.*, **113**, 4392-4397.
 - 18 Bağcıoğlu M, Kohler A, Seifert S, Kneipp J, Zimmermann B and McMahon S, 2017, Monitoring of plant-environment interactions by high-throughput FTIR spectroscopy of pollen, *Methods Ecol. Evol.*, **8**, 870-880.
 - 19 Bai KX, Chang NB and Gao W, 2016, Quantification of relative contribution of Antarctic ozone depletion to increased austral extratropical precipitation during 1979-2013, *J. Geophys. Res. Atmos.*, **121**, 1459-1474.
 - 20 Bais AF, Lucas RM, Bornman JF, Williamson CE, Sulzberger B, Austin AT, Wilson SR, Andrady AL, Bernhard G, McKenzie RL, Aucamp PJ, Madronich S, Neale RE, Yazar S, Young AR, de Gruijl FR, Norval M, Takizawa Y, Barnes PW, Robson TM, Robinson SA, Ballaré CL, Flint SD, Neale PJ, Hylander S, Rose KC, Wangberg SA, Häder D-P, Worrest RC, Zepp RG, Paul ND, Cory RM, Solomon KR, Longstreth J, Pandey KK, Redhwi HH, Torikai A and Heikkilä AM, 2018, Environmental effects of ozone depletion, UV radiation and interactions with climate change: UNEP Environmental Effects Assessment Panel, update 2017, *Photochem. Photobiol. Sci.*, **17**, 127-179.
 - 21 Bais AF, McKenzie RL, Bernhard G, Aucamp PJ, Ilyas M, Madronich S and Tourpali K, 2015, Ozone depletion and climate change: Impacts on UV radiation, *Photochem. Photobiol. Sci.*, **14**, 19-52.
 - 22 Baker NR and Allison SD, 2015, Ultraviolet photodegradation facilitates microbial litter decomposition in a Mediterranean climate, *Ecol.*, **96**, 1994-2003.
 - 23 Baldocchi D, Hutchison B, Matt D and McMillen R, 1984, Seasonal variations in the radiation regime within an oak-hickory forest, *Agric. Forest Meteorol.*, **33**, 177-191.
 - 24 Ballaré CL, 2014, Light regulation of plant defense, *Annu. Rev. Plant Biol.*, **65**, 335-363.
 - 25 Ballaré CL and Austin AT, 2017, UV radiation and terrestrial ecosystems: Emerging perspectives, in *UV-B Radiation and Plant Life: Molecular Biology to Ecology* ed.: Jordan B, CABI, Oxfordshire, UK, pp. 23-38.
 - 26 Ballaré CL, Caldwell MM, Flint SD, Robinson SA and Bornman JF, 2011, Effects of solar ultraviolet radiation on terrestrial ecosystems. Patterns, mechanisms, and interactions with climate change, *Photochem. Photobiol. Sci.*, **10**, 226-241.
 - 27 Ballaré CL, Mazza CA, Austin AT and Pierik R, 2012, Canopy light and plant health, *Plant Physiol.*, **160**, 145-155.

- 28 Ballaré CL and Pierik R, 2017, The shade-avoidance syndrome: multiple signals and ecological consequences, *Plant Cell Environ.*, **40**, 2530-2543.
- 29 Bancroft BA, Baker NJ and Blaustein AR, 2008, A meta-analysis of the effects of ultraviolet B radiation and its synergistic interactions with pH, contaminants, and disease on amphibian survival, *Conserv. Biol.*, **22**, 987-96.
- 30 Bandoro J, Solomon S, Donohoe A, Thompson DWJ and Santer BD, 2014, Influences of the Antarctic Ozone Hole on Southern Hemispheric Summer Climate Change, *J. Climate*, **27**, 6245-6264.
- 31 Bandurska H, Niedziela J and Chadzinikolau T, 2013, Separate and combined responses to water deficit and UV-B radiation, *Plant Sci.*, **213**, 98-105.
- 32 Barnes PW, 2017, Understanding the ecological role of solar ultraviolet radiation in the life (and death) of terrestrial plants: An historical perspective, *UV4Plants Bull.*, **2**, 7-15.
- 33 Barnes PW, Flint SD, Ryel RJ, Tobler MA, Barkley AE and Wargent JJ, 2015, Rediscovering leaf optical properties: New insights into plant acclimation to solar UV radiation, *Plant Physiol. Biochem.*, **93**, 94-100.
- 34 Barnes PW, Flint SD, Tobler MA and Ryel RJ, 2016, Diurnal adjustment in UV-sunscreen protection is widespread among higher plants, *Oecologia*, **181**, 55-63.
- 35 Barnes PW, Kersting AR, Flint SD, Beyschlag W and Ryel RJ, 2013, Adjustments in epidermal UV-transmittance of leaves in sun-shade transitions, *Physiol. Plant.*, **149**, 200-213.
- 36 Barnes PW, Robson TM, Tobler MA, Bottger IN and Flint SD, 2017, Plant responses to fluctuating UV environments, in *UV-B Radiation and Plant Life: Molecular Biology to Ecology* ed.: Jordan B, CABI, Oxfordshire, UK, pp. 72-89.
- 37 Barnes PW, Shinkle JR, Flint SD and Ryel RJ, 2005, UV-B radiation, photomorphogenesis and plant-plant interactions, *Prog. Botany*, **66**, 313-340.
- 38 Barnes PW, Throop HL, Archer SR, Breshears DD, McCulley RL and Tobler MA, 2015, Sunlight and soil-litter mixing: drivers of litter decomposition in drylands, *Prog. Botany*, **76**, 273-302.
- 39 Barnes PW, Throop HL, Hewins DB, Abbene ML and Archer SR, 2012, Soil coverage reduces photodegradation and promotes the development of soil-microbial films on dryland leaf litter, *Ecosystems*, **15**, 311-321.
- 40 Beckmann M, Hock M, Bruelheide H and Erfmeier A, 2012, The role of UV-B radiation in the invasion of *Hieracium pilosella*-A comparison of German and New Zealand plants, *Environ. Exp. Bot.*, **75**, 173-180.
- 41 Bergstrom DM, Bricher PK, Raymond B, Terauds A, Doley D, McGeoch MA, Whinam J, Glen M, Yuan Z, Kiefer K, Shaw Justine D, Bramely-Alves J, Rudman T, Mohammed C, Lucieer A, Visoiu M, Jansen van Vuuren B and Ball MC, 2015, Rapid collapse of a sub-Antarctic alpine ecosystem: the role of climate and pathogens, *J. Appl. Ecol.*, **52**, 774-783.
- 42 Bernula P, Crocco CD, Arongaus AB, Ulm R, Nagy F and Viczián A, 2017, Expression of the UVR8 photoreceptor in different tissues reveals tissue-autonomous features of UV-B signalling, *Plant Cell Environ.*, **40**, 1104-1114.

- 43 Biever JJ, Brinkman D and Gardner G, 2014, UV-B inhibition of hypocotyl growth in etiolated *Arabidopsis thaliana* seedlings is a consequence of cell cycle arrest initiated by photodimer accumulation, *J. Exp. Bot.*, **65**, 2949-2961.
- 44 Biever JJ and Gardner G, 2016, The relationship between multiple UV-B perception mechanisms and DNA repair pathways in plants, *Environ. Exp. Bot.*, **124**, 89-99.
- 45 Bjorkman AD, Vellend M, Frei ER and Henry GHR, 2017, Climate adaptation is not enough: warming does not facilitate success of southern tundra plant populations in the high Arctic, *Glob. Change Biol.*, **23**, 1540-1551.
- 46 Björn LO, 2015, On the history of phyto-photo UV science (not to be left in skoto toto and silence), *Plant Physiol. Biochem.*, **93**, 3-8.
- 47 Blaustein AR and Kats LB, 2003, Amphibians in a very bad light, *Bioscience*, **53**, 1028-1029.
- 48 Blumthaler M, Ambach W and Ellinger R, 1997, Increase in solar UV radiation with altitude, *J. Photochem. Photobiol. B.*, **39**, 130-134.
- 49 Bond DPG and Grasby SE, 2017, On the causes of mass extinctions, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **478**, 3-29.
- 50 Bornman JF, Barnes PW, Robinson SA, Ballaré CL, Flint SD and Caldwell MM, 2015, Solar ultraviolet radiation and ozone depletion-driven climate change: effects on terrestrial ecosystems, *Photochem. Photobiol. Sci.*, **14**, 88-107.
- 51 Bornman JF and Vogelmann TC, 1988, Penetration of blue and UV radiation measured by fiber optics in spruce and fir needles, *Physiol. Plant.*, **72**, 699-705.
- 52 Bosco T, Bertiller MB and Carrera AL, 2016, Combined effects of litter features, UV radiation, and soil water on litter decomposition in denuded areas of the arid Patagonian Monte, *Plant Soil*, **406**, 71-82.
- 53 Both C and teMarvelde L, 2007, Climate change and timing of avian breeding and migration throughout Europe, *Clim. Res.*, **35**, 93-105.
- 54 Brandt LA, Bohnet C and King JY, 2009, Photochemically induced carbon dioxide production as a mechanism for carbon loss from plant litter in arid ecosystems, *J. Geophys. Res. Biogeosci.*, **114**, G02004.
- 55 Bravo-Oviedo A, Ruiz-Peinado R, Onrubia R and del Río M, 2017, Thinning alters the early-decomposition rate and nutrient immobilization-release pattern of foliar litter in Mediterranean oak-pine mixed stands, *Forest Ecol. Manag.*, **391**, 309-320.
- 56 Brelsford CC and Robson TM, 2018, Blue light advances bud burst in branches of three deciduous tree species under short-day conditions, *Trees*, **32**, 1157-1164.
- 57 Brodersen CR, Vogelmann TC, Williams WE and Gorton HL, 2008, A new paradigm in leaf-level photosynthesis: direct and diffuse lights are not equal, *Plant Cell. Environ.*, **31**, 159-164.
- 58 Bronnimann S, Jacques-Coper M, Rozanov E, Fischer AM, Morgenstern O, Zeng G, Akiyoshi H and Yamashita Y, 2017, Tropical circulation and precipitation response to ozone depletion and recovery, *Environ. Res. Lett.*, **12**, 064011.

- 59 Brown MJ, Parker GG and Posner NE, 1994, A survey of ultraviolet-B radiation in forests, *J. Ecol.*, **82**, 843-854.
- 60 Caldwell MM, 1971, Solar UV irradiation and the growth and development of higher plants, *Photophysiol.*, **6**, 131-177.
- 61 Caldwell MM, Bornman JF, Ballaré CL, Flint SD and Kulandaivelu G, 2007, Terrestrial ecosystems, increased solar ultraviolet radiation, and interactions with other climate change factors, *Photochem. Photobiol. Sci.*, **6**, 252-266.
- 62 Caldwell MM, Robberecht R and Billings WD, 1980, A steep latitudinal gradient of solar ultraviolet-B radiation in the arctic-alpine life zone, *Ecol.*, **61**, 600-611.
- 63 Caldwell MM, Searles PS, Flint SD and Barnes PW, 1999, Terrestrial ecosystem responses to solar UV-B radiation mediated by vegetation, microbes and abiotic photochemistry, in *Physiological Plant Ecology* eds.: Press MC, Scholes JD and Barker MG, Blackwell Science Ltd., Oxford, pp. 241-262.
- 64 Caputo C, Rutitzky M and Ballaré CL, 2006, Solar ultraviolet-B radiation alters the attractiveness of *Arabidopsis* plants to diamondback moths (*Plutella xylostella* L.): impacts on oviposition and involvement of the jasmonic acid pathway, *Oecologia*, **149**, 81-90.
- 65 Carbonell-Bejerano P, Diago MP, Martinez-Abaigar J, Martinez-Zapater JM, Tardaguila J and Nunez-Olivera E, 2014, Solar ultraviolet radiation is necessary to enhance grapevine fruit ripening transcriptional and phenolic responses, *BMC Plant Biol.*, **14**, 183.
- 66 Carvalho T, Becker CG and Toledo LF, 2017, Historical amphibian declines and extinctions in Brazil linked to chytridiomycosis, *Proc. Biol. Sci.*, **284**.
- 67 Castagna A, Csepregi K, Neugart S, Zipoli G, Večeřová K, Jakab G, Jug T, Llorens L, Martínez-Abaigar J, Martínez-Lüscher J, Núñez-Olivera E, Ranieri A, Schoedl-Hummel K, Schreiner M, Teszlák P, Tittmann S, Urban O, Verdaguer D, Jansen MAK and Hideg É, 2017, Environmental plasticity of Pinot noir grapevine leaves; a trans-European study of morphological and biochemical changes along a 1500 km latitudinal climatic gradient, *Plant Cell Environ.*, **40**, 2790-2805.
- 68 Cataldo M, Evangelista H, Simoes JC, Godoi RHM, Simmonds I, Hollanda MH, Wainer I, Aquino F and Van Grieken R, 2013, Mineral dust variability in central West Antarctica associated with ozone depletion, *Atmos. Chem. Phys.*, **13**, 2165-2175.
- 69 Ceppi P and Hartmann DL, 2012, On the speed of the eddy-driven jet and the width of the Hadley Cell in the Southern Hemisphere, *J. Climate*, **26**, 3450-3465.
- 70 Chen M, Parton WJ, Adair EC, Asao S, Hartman MD and Gao W, 2016, Simulation of the effects of photodecay on long-term litter decay using DayCent, *Ecosphere*, **7**, e01631.
- 71 Cheng SJ, Bohrer G, Steiner AL, Hollinger DY, Suyker A, Phillips RP and Nadelhoffer KJ, 2015, Variations in the influence of diffuse light on gross primary productivity in temperate ecosystems, *Agric. Forest Meteorol.*, **201**, 98-110.

- 72 Chiodo G and Polvani Lorenzo M, 2017, Reduced Southern Hemispheric circulation response to quadrupled CO₂ due to stratospheric ozone feedback, *Geophys. Res. Lett.*, **44**, 465-474.
- 73 Clarke LJ, Robinson SA, Hua Q, Ayre DJ and Fink D, 2012, Radiocarbon bomb spike reveals biological effects of Antarctic climate change, *Glob. Change Biol.*, **18**, 301-310.
- 74 Cleland EE, Chuine I, Menzel A, Mooney HA and Schwartz MD, 2007, Shifting plant phenology in response to global change, *Trend. Ecol. Evolut.*, **22**, 357-65.
- 75 Clem KR, Renwick JA, McGregor J and Fogt RL, 2016, The relative influence of ENSO and SAM on Antarctic Peninsula climate, *J. Geophys. Res. Atmos.*, **121**, 9324-9341.
- 76 Coffey A, Prinsen E, Jansen MAK and Conway J, 2017, The UVB photoreceptor UVR8 mediates accumulation of UV-absorbing pigments, but not changes in plant morphology, under outdoor conditions, *Plant Cell Environ.*, **40**, 2250-2260.
- 77 Cohen JM, Lajeunesse MJ and Rohr JR, 2018, A global synthesis of animal phenological responses to climate change, *Nat. Clim. Change*, **8**, 224-228.
- 78 Colesie C, Büdel B, Hurry V and Green TGA, 2017, Can Antarctic lichens acclimatize to changes in temperature?, *Glob. Change Biol.*, **24**, 1123-1135.
- 79 Convey P, Chown SL, Clarke A, Barnes DKA, Bokhorst S, Cummings V, Ducklow HW, Frati F, Green TGA, Gordon S, Griffiths HJ, Howard-Williams C, Huiskes AHL, Laybourn-Parry J, Lyons WB, McMin A, Morley SA, Peck LS, Quesada A, Robinson SA, Schiaparelli S and Wall DH, 2014, The spatial structure of Antarctic biodiversity, *Ecol. Monogr.*, **84**, 203-244.
- 80 Coviaga C, Rizzo A, Perez P, Daga R, Poire D, Cusminsky G and Guevara SR, 2017, Reconstruction of the hydrologic history of a shallow Patagonian steppe lake during the past 700 yr, using chemical, geologic, and biological proxies, *Quat. Res.*, **87**, 208-226.
- 81 Cuthill IC, Allen WL, Arbuckle K, Caspers B, Chaplin G, Hauber ME, Hill GE, Jablonski NG, Jiggins CD, Kelber A, Mappes J, Marshall J, Merrill R, Osorio D, Prum R, Roberts NW, Roulin A, Rowland HM, Sherratt TN, Skelhorn J, Speed MP, Stevens M, Stoddard MC, Stuart-Fox D, Talas L, Tibbetts E and Caro T, 2017, The biology of color, *Science*, **357**, eaan0221.
- 82 Cuyckens GAE, Christie DA, Domic AI, Malizia LR and Renison D, 2016, Climate change and the distribution and conservation of the world's highest elevation woodlands in the South American Altiplano, *Glob. Planet. Change*, **137**, 79-87.
- 83 Dainese M, Aikio S, Hulme PE, Bertolli A, Prosser F and Marini L, 2017, Human disturbance and upward expansion of plants in a warming climate, *Nat. Clim. Change*, **7**, 577-580.
- 84 Davidson AM, Jennions M and Nicotra AB, 2011, Do invasive species show higher phenotypic plasticity than native species and, if so, is it adaptive? A meta-analysis, *Ecol. Lett.*, **14**, 419-431.
- 85 Day TA, Guénou R and Ruhland CT, 2015, Photodegradation of plant litter in the Sonoran Desert varies by litter type and age, *Soil Biol. Biochem.*, **89**, 109-122.

- 86 Day TA, Vogelmann TC and DeLucia EH, 1992, Are some plant life forms more effective than others in screening out ultraviolet-B radiation?, *Oecologia*, **92**, 513-519.
- 87 de Zwaan Devin R, Greenwood Jennifer L and Martin K, 2016, Feather melanin and microstructure variation in dark-eyed junco *Junco hyemalis* across an elevational gradient in the Selkirk Mountains, *J. Avian Biol.*, **48**, 552-562.
- 88 Del-Castillo-Alonso MÁ, Castagna A, Csepregi K, Hideg É, Jakab G, Jansen MA, Jug Ta, Llorens L, Mátaí A and Martínez-Lüscher J, 2016, Environmental factors correlated with the metabolite profile of *Vitis vinifera* cv. Pinot Noir berry skins along a European latitudinal gradient, *J. Agric. Food. Chem.*, **64**, 8722-8734.
- 89 Demchik SM and Day TA, 1996, Effect of enhanced UV-B radiation on pollen quantity, quality, and seed yield in *Brassica rapa* (Brassicaceae), *Am. J. Bot.*, **83**, 573-579.
- 90 Demkura PV, Abdala G, Baldwin IT and Ballaré CL, 2010, Jasmonate-dependent and -independent pathways mediate specific effects of solar ultraviolet B radiation on leaf phenolics and antiherbivore defense, *Plant Physiol.*, **152**, 1084-1095.
- 91 Demkura PV and Ballaré CL, 2012, UVR8 mediates UV-B-induced Arabidopsis defense responses against *Botrytis cinerea* by controlling sinapate accumulation, *Molecular Plant*, **5**, 642-52.
- 92 Dengel S, Grace J, Aakala T, Hari P, Newberry SL and Mizunuma T, 2013, Spectral characteristics of pine needles at the limit of tree growth in subarctic Finland, *Plant Ecol. Divers.*, **6**, 31-44.
- 93 Dennison FW, McDonald A and Morgenstern O, 2016, The influence of ozone forcing on blocking in the Southern Hemisphere, *J. Geophys. Res. Atmos.*, **121**, 14,358-14,371.
- 94 Deppeler SL and Davidson AT, 2017, Southern ocean phytoplankton in a changing climate, *Front Mar Sci*, **4**, 40.
- 95 Di Ferdinando M, Brunetti C, Agati G and Tattini M, 2014, Multiple functions of polyphenols in plants inhabiting unfavorable Mediterranean areas, *Environ. Exp. Bot.*, **103**, 107-116.
- 96 Díaz LB and Vera CS, 2017, Austral summer precipitation interannual variability and trends over Southeastern South America in CMIP5 models, *Int. J. Climatol.*, **37**, 681-695.
- 97 Diehl JJE, Baines FM, Heijboer AC, Leeuwen JP, Kik M, Hendriks WH and Oonincx DGAB, 2018, A comparison of UVb compact lamps in enabling cutaneous vitamin D synthesis in growing bearded dragons, *J. Anim. Physiol. Anim. Nutr.*, **102**, 308-316.
- 98 Dillon FM, Tejedor MD, Ilina N, Chludil HD, Mithöfer A, Pagano EA and Zavala JA, 2018, Solar UV-B radiation and ethylene play a key role in modulating effective defenses against *Anticarsia gemmatilis* larvae in field-grown soybean, *Plant Cell Environ.*, **41**, 383-394.

- 99 Dinh ST, Gális I and Baldwin IT, 2013, UVB radiation and 17-hydroxygeranyllinalool diterpene glycosides provide durable resistance against mirid (*Tupiocoris notatus*) attack in field-grown *Nicotiana attenuata* plants, *Plant Cell Environ.*, **36**, 590-606.
- 100 Elfadly E, Abd El-Aal H, Rizk A and Sobeih W, 2016, Ambient UV manipulation in greenhouses: plant responses and insect pest management in cucumber, 1134 ed., International Society for Horticultural Science (ISHS), Leuven, Belgium, pp. 343-350.
- 101 Emde C, Buras-Schnell R, Kylling A, Mayer B, Gasteiger J, Hamann U, Kylling J, Richter B, Pause C, Dowling T and Bugliaro L, 2016, The libRadtran software package for radiative transfer calculations (version 2.0.1), *Geosci. Model Dev.*, **9**, 1647-1672.
- 102 Epstein HE and Bhatt US, 2015, Tundra Greenness, NOAA, <http://www.arctic.noaa.gov/reportcard/>, accessed December 18, 2015,
- 103 Erickson DJ, Sulzberger B, Zepp RG and Austin AT, 2015, Effects of stratospheric ozone depletion, solar UV radiation, and climate change on biogeochemical cycling: interactions and feedbacks, *Photochem. Photobiol. Sci.*, **14**, 127-148.
- 104 Escobar-Bravo R, Klinkhamer PGL and Leiss KA, 2017, Interactive effects of UV-B light with abiotic factors on plant growth and chemistry, and their consequences for defense against arthropod herbivores, *Front. Plant. Sci.*, **8**, 278.
- 105 Fasano R, Gonzalez N, Tosco A, Dal Piaz F, Docimo T, Serrano R, Grillo S, Leone A and Inze D, 2014, Role of Arabidopsis UV RESISTANCE LOCUS 8 in Plant Growth Reduction under Osmotic Stress and Low Levels of UV-B, *Molecular Plant*, **7**, 773-791.
- 106 Feister U, Cabrol N and Hader D, 2015, UV irradiance enhancements by scattering of solar radiation from clouds, *Atmosphere*, **6**, 1211-1228.
- 107 Féret JB, Gitelson AA, Noble SD and Jacquemoud S, 2017, PROSPECT-D: Towards modeling leaf optical properties through a complete lifecycle, *Rem. Sens. Environ.*, **193**, 204-215.
- 108 Field CB and Ehleringer JR, 1993, Introduction: questions of scale, in *Scaling Physiological Processes*, Elsevier, pp. 1-4.
- 109 Fina J, Casadevall R, Abdelgawad H, Prinsen E, Markakis MN, Beemster GTS and Casati P, 2017, UV-B inhibits leaf growth through changes in growth regulating factors and gibberellin levels, *Plant Physiol.*, **174**, 1110.
- 110 Fiscus EL and Booker FL, 1995, Is increased UV-B a threat to crop photosynthesis and productivity?, *Photosyn. Res.*, **43**, 81-92.
- 111 Flint SD and Caldwell MM, 1996, Scaling plant ultraviolet spectral responses from laboratory action spectra to field spectral weighting factors, *J. Plant Physiol.*, **148**, 107-114.
- 112 Flint SD and Caldwell MM, 1998, Solar UV-B and visible radiation in tropical forest gaps: measurements partitioning direct and diffuse radiation, *Glob. Change Biol.*, **4**, 863-870.

- 113 Flint SD and Caldwell MM, 2003, A biological spectral weighting function for ozone depletion research with higher plants, *Physiol Plant*, **117**, 137-144.
- 114 Franco-Belussi L, Fanali LZ and De Oliveira C, 2018, UV-B affects the immune system and promotes nuclear abnormalities in pigmented and non-pigmented bullfrog tadpoles, *J Photochem Photobiol B*, **180**, 109-117.
- 115 Fraser WT, Lomax BH, Jardine PE, Gosling WD and Sephton MA, 2014, Pollen and spores as a passive monitor of ultraviolet radiation, *Front. Ecol. Evolut.*, **2**.
- 116 Frenot Y, Chown SL, Whinam J, Selkirk PM, Convey P, Skotnicki M and Bergstrom DM, 2005, Biological invasions in the Antarctic: extent, impacts and implications, *Biol. Rev.*, **80**, 45-72
- 117 Fu G and Shen Z-X, 2017, Effects of enhanced UV-B radiation on plant physiology and growth on the Tibetan Plateau: a meta-analysis, *Acta Physiol. Plant.*, **39**, 85.
- 118 Galván I, Jorge A, Pacheco C, Spencer D, Halley DJ, Itty C, Kornan J, Nielsen JT, Ollila T, Sein G, Stój M and Negro JJ, 2018, Solar and terrestrial radiations explain continental-scale variation in bird pigmentation, *Oecologia*, **188**, 683–693.
- 119 Gastellu-Etchegorry JP, Lauret N, Yin T, Landier L, Kallel A, Malenovský Z, Bitar AA, Aval J, Benhmida S, Qi J, Medjdoub G, Guilleux J, Chavanon E, Cook B, Morton D, Chrysoulakis N and Mitraka Z, 2017, DART: Recent Advances in Remote Sensing Data Modeling With Atmosphere, Polarization, and Chlorophyll Fluorescence, *IEEE J. Select. Top. Appl. Earth Obs. Remote Sens.*, **10**, 2640-2649.
- 120 Gliksman D, Rey A, Seligmann R, Dumbur R, Sperling O, Navon Y, Haenel S, De Angelis P, Arnone John A and Grünzweig José M, 2017, Biotic degradation at night, abiotic degradation at day: positive feedbacks on litter decomposition in drylands, *Glob. Change Biol.*, **23**, 1564-1574.
- 121 Gonzalez PLM, Polvani LM, Seager R and Correa GJP, 2014, Stratospheric ozone depletion: a key driver of recent precipitation trends in South Eastern South America, *Clim. Dyn.*, **42**, 1775-1792.
- 122 Grant RH, Apostol K and Gao W, 2005, Biologically effective UV-B exposures of an oak-hickory forest understory during leaf-out, *Agric. Forest Meteorol.*, **132**, 28-43.
- 123 Grašič M, Budak V, Klančnik K and Gaberščik A, 2017, Optical properties of halophyte leaves are affected by the presence of salt on the leaf surface, *Biologia*, **72**, 1131.
- 124 Greene AM, Goddard L, Gonzalez PLM, Ines AVM and Chrysanthacopoulos J, 2015, A climate generator for agricultural planning in southeastern South America, *Agric. Forest Meteorol.*, **203**, 217-228.
- 125 Guillermo-Ferreira R, Therézio EM, Gehlen MH, Bispo PC and Marletta A, 2014, The role of wing pigmentation, UV and fluorescence as signals in a neotropical damselfly, *J. Insect Behav.*, **27**, 67-80.
- 126 Gwynn-Jones D, Jones AG, Waterhouse A, Winters A, Comont D, Scullion J, Gardias R, Graae BJ, Lee JA and Callaghan TV, 2012, Enhanced UV-B and elevated CO₂ impacts sub-Arctic shrub berry abundance, quality and seed germination, *Ambio*, **41**, 256-268.

- 127 Hantson S, Knorr W, Schurgers G, Pugh TAM and Arneth A, 2017, Global isoprene and monoterpene emissions under changing climate, vegetation, CO₂ and land use, *Atmos. Environ.*, **155**, 35-45.
- 128 Hartikainen SM, Jach A, Grané A and Robson TM, 2018, Assessing scale-wise similarity of curves with a thick pen: As illustrated through comparisons of spectral irradiance, *Ecol. Evol.*, **8**, 10206–10218.
- 129 Hayes S, Velanis CN, Jenkins GI and Franklin KA, 2014, UV-B detected by the UVR8 photoreceptor antagonizes auxin signaling and plant shade avoidance, *Proc. Nat. Acad. Sci. USA.*, **111**, 11894-11899.
- 130 Heinze M, Hanschen FS, Wiesner-Reinhold M, Baldermann S, Grafe J, Schreiner M and Neugart S, 2018, Effects of developmental stages and reduced UVB and low UV conditions on plant secondary metabolite profiles in pak choi (*Brassica rapa* subsp. *chinensis*), *J Agric Food Chem*, **66**, 1678-1692.
- 131 Hendon HH, Lim E-P, Arblaster JM and Anderson DLT, 2014, Causes and predictability of the record wet east Australian spring 2010, *Clim. Dyn.*, **42**, 1155-1174.
- 132 Hendon HH, Thompson DWJ and Wheeler MC, 2007, Australian rainfall and surface temperature variations associated with the Southern Hemisphere Annular Mode, *J. Climate*, **20**, 2452–2467.
- 133 Henry-Kirk R, A., Plunkett B, Hall M, McGhie T, Allan Andrew C, Wargent Jason J and Espley Richard V, 2018, Solar UV light regulates flavonoid metabolism in apple (*Malus x domestica*), *Plant Cell Environ.*, **41**, 675-688.
- 134 Hernández JA, Diaz-Vivancos P, Barba-Espín G and Clemente-Moreno MJ, 2017, On the role of salicylic acid in plant responses to environmental stresses, in *Salicylic Acid: A Multifaceted Hormone* eds.: Nazar R, Iqbal N and Khan NA, Springer Singapore, Singapore, pp. 17-34.
- 135 Hessler A, Allen KJ, Vance T, Abram NJ and Saunders KM, 2017, Reconstructions of the southern annular mode (SAM) during the last millennium, *Prog. Phys. Geog.*, **41**, 834-849.
- 136 Hewins DB, Sinsabaugh RL, Archer SR and Throop HL, 2017, Soil–litter mixing and microbial activity mediate decomposition and soil aggregate formation in a sandy shrub-invaded Chihuahuan Desert grassland, *Plant Ecol.*, **218**, 459-474.
- 137 Hewins DB and Throop HL, 2016, Leaf litter decomposition is rapidly enhanced by the co-occurrence of monsoon rainfall and soil-litter mixing across a gradient of coppice dune development in the Chihuahuan Desert, *J. Arid. Environ.*, **129**, 111-118.
- 138 Hideg E, Jansen MAK and Strid A, 2013, UV-B exposure, ROS, and stress: inseparable companions or loosely linked associates?, *Trends Plant Sci.*, **18**, 107-115.
- 139 Hock M, Beckmann M, Hofmann RW, Bruehlheide H and Erfmeier A, 2015, Effects of UV-B radiation on germination characteristics in invasive plants in New Zealand, *Neobiota*, **26**, 21-37.

- 140 Hodgson DA, Roberts D, McMinn A, Verleyen E, Terry B, Corbett C and Vyverman W, 2006, Recent rapid salinity rise in three East Antarctic lakes, *J. Paleolimnol.*, **36**, 385-406.
- 141 Holland MM, Landrum L, Raphael M and Stammerjohn S, 2017, Springtime winds drive Ross Sea ice variability and change in the following autumn, *Nat. Commun.*, **8**, 731.
- 142 Holopainen JK, Kivimäenpää M and Julkunen-Tiitto R, 2018, New light for phytochemicals, *Trends Biotech.*, **36**, 7-10.
- 143 Holz A, Paritsis J, Mundo IA, Veblen TT, Kitzberger T, Williamson GJ, Aráoz E, Bustos-Schindler C, González ME, Grau HR and Quezada JM, 2017, Southern Annular Mode drives multicentury wildfire activity in southern South America, *Proc. Nat. Acad. Sci. USA.*, **114**, 9552-9557.
- 144 Holz A and Veblen TT, 2011, Variability in the Southern Annular Mode determines wildfire activity in Patagonia, *Geophys. Res. Lett.*, **38**.
- 145 Huang G and Li Y, 2017, Photodegradation effects are related to precipitation amount, precipitation frequency and litter traits in a desert ecosystem, *Soil Biol. Biochem.*, **115**, 383-392.
- 146 Huché-Théliér L, Crespel L, Gourrierc JL, Morel P, Sakr S and Leduc N, 2016, Light signaling and plant responses to blue and UV radiations—Perspectives for applications in horticulture, *Environ. Exp. Bot.*, **121**, 22-38.
- 147 Ibañez VN, Berli FJ, Masuelli RW, Bottini RA and Marfil CF, 2017, Influence of altitude and enhanced ultraviolet-B radiation on tuber production, seed viability, leaf pigments and morphology in the wild potato species *Solanum kurtzianum* Bitter & Wittm collected from an elevational gradient, *Plant Sci.*, **261**, 60-68.
- 148 Ilić ZS and Fallik E, 2017, Light quality manipulation improves vegetable quality at harvest and postharvest: A review, *Environ. Exp. Bot.*, **139**, 79-90.
- 149 IPCC, 2014, *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- 150 Ivy DJ, Hilgenbrink C, Kinnison D, Alan Plumb R, Sheshadri A, Solomon S and Thompson DWJ, 2017, Observed Changes in the Southern Hemispheric Circulation in May, *J. Climate*, **30**, 527-536.
- 151 Ivy DJ, Solomon S, Kinnison D, Mills MJ, Schmidt A and Neely RR, 2017, The influence of the Calbuco eruption on the 2015 Antarctic ozone hole in a fully coupled chemistry-climate model, *Geophys. Res. Lett.*, **44**, 2556-2561.
- 152 Izaguirre MM, Mazza CA, Biondini M, Baldwin IT and Ballaré CL, 2006, Remote sensing of future competitors: Impacts on plant defenses, *Proc. Nat. Acad. Sci. USA.*, **103**, 7170-7174.

- 153 Izaguirre MM, Mazza CA, Svatos A, Baldwin IT and Ballaré CL, 2007, Solar ultraviolet-B radiation and insect herbivory trigger partially overlapping phenolic responses in *Nicotiana attenuata* and *Nicotiana longiflora*, *Ann. Bot.*, **99**, 103-109.
- 154 Izaguirre MM, Scopel AL, Baldwin IT and Ballaré CL, 2003, Convergent responses to stress. Solar ultraviolet-B radiation and *Manduca sexta* herbivory elicit overlapping transcriptional responses in field-grown plants of *Nicotiana longiflora*, *Plant Physiol*, **132**, 1755-1767.
- 155 Jansen MAK and Bornman JF, 2012, UV-B radiation: from generic stressor to specific regulator, *Physiol. Plant.*, **145**, 501-504.
- 156 Jansen MAK and Urban O, 2017, UV-B-induced morphological changes—an enigma in *UV-B radiation and plant life: Molecular biology to ecology*. ed.: Jordan BR, CABI, Oxfordshire, UK, pp. 58-71.
- 157 Jardine PE, Abernethy FAJ, Lomax BH, Gosling WD and Fraser WT, 2017, Shedding light on sporopollenin chemistry, with reference to UV reconstructions, *Rev. Palaeobot. Palynol.*, **238**, 1-6.
- 158 Jardine PE, Fraser WT, Lomax BH, Sephton MA, Shanahan TM, Miller CS and Gosling WD, 2016, Pollen and spores as biological recorders of past ultraviolet irradiance, *Sci. Rep.*, **6**, 39269.
- 159 Jenkins GI, 2014, The UV-B Photoreceptor UVR8: From Structure to Physiology, *Plant Cell*, **26**, 21-37.
- 160 Jenkins GI, 2017, Photomorphogenic responses to ultraviolet-B light, *Plant Cell Environ.*, **40**, 2544-2557.
- 161 Jones TR, Roberts WHG, Steig EJ, Cuffey KM, Markle BR and White JWC, 2018, Southern Hemisphere climate variability forced by Northern Hemisphere ice-sheet topography, *Nature*, **554**, 351-355.
- 162 Jordan BR, 2017, *UV-B radiation and plant life: Molecular biology to ecology*, CABI Press, Wallingford, UK.
- 163 Julkunen-Tiitto R, Nenadis N, Neugart S, Robson M, Agati G, Vepsäläinen J, Zipoli G, Nybakken L, Winkler B and Jansen MAK, 2015, Assessing the response of plant flavonoids to UV radiation: an overview of appropriate techniques, *Phytochem. Rev.*, **14**, 273-297.
- 164 Kang SM, Polvani LM, Fyfe JC and Sigmond M, 2011, Impact of polar ozone depletion on subtropical precipitation, *Nat. Geosci.*, **332**, 951-954.
- 165 Kang SM, Polvani LM, Fyfe JC, Son SW, Sigmond M and Correa GJP, 2013, Modeling evidence that ozone depletion has impacted extreme precipitation in the austral summer, *Geophys. Res. Lett.*, **40**, 4054-4059.
- 166 King JY, Brandt LA and Adair EC, 2012, Shedding light on plant litter decomposition: advances, implications and new directions in understanding the role of photodegradation, *Biogeochemistry*, **111**, 57-81.
- 167 Kohler H, Contreras RA, Pizarro M, Cortes-Antiquera R and Zuniga GE, 2017, Antioxidant responses induced by UVB radiation in *Deschampsia antarctica* Desv, *Front. Plant. Sci.*, **8**, 921.

- 168 Körner C, 2003, *Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystems*, 2nd ed., Springer-Verlag, New York.
- 169 Körner C, 2007, The use of 'altitude' in ecological research, *Trend. Ecol. Evolut.*, **22**, 569-574.
- 170 Körner C and Basler D, 2010, Phenology under global warming, *Science*, **327**, 1461.
- 171 Kostov Y, Marshall J, Hausmann U, Armour KC, Ferreira D and Holland MM, 2017, Fast and slow responses of Southern Ocean sea surface temperature to SAM in coupled climate models, *Clim. Dyn.*, **48**, 1595-1609.
- 172 Kovács V, Gondor OK, Szalai G, Majláth I, Janda T and Pál M, 2014, UV-B radiation modifies the acclimation processes to drought or cadmium in wheat, *Environ. Exp. Bot.*, **100**, 122-131.
- 173 Krause GH, Grube E, Koroleva OY, Barth C and Winter K, 2004, Do mature shade leaves of tropical tree seedlings acclimate to high sunlight and UV radiation?, *Funct. Plant Biol.*, **31**, 743-756.
- 174 Krause GH, Grube E, Virgo A and Winter K, 2003, Sudden exposure to solar UV-B radiation reduces net CO₂ uptake and photosystem I efficiency in shade-acclimated tropical tree seedlings, *Plant Physiol.*, **131**, 745-752.
- 175 Kronfeld-Schor N, Visser ME, Salis L and van Gils JA, 2017, Chronobiology of interspecific interactions in a changing world, *Philos. Trans. Roy. Soc. Lond. B.*, **372**.
- 176 Kuhlmann F and Muller C, 2009, Development-dependent effects of UV radiation exposure on broccoli plants and interactions with herbivorous insects, *J. Environ. Exp. Bot.*, **66**, 61-68.
- 177 Kuhlmann F and Müller C, 2010, UV-B impact on aphid performance mediated by plant quality and plant changes induced by aphids, *Plant Biol.*, **12**, 676-684.
- 178 Kwon JK, Khoshimkhujaev B, Lee JH, Yu IH, Park KS and Choi HG, 2017, Growth and yield of tomato and cucumber plants in polycarbonate or glass greenhouses, *Korean J. Hort. Sci.*, **35**, 79-87.
- 179 Lapidot M, Legg JP, Wintermantel WM and Polston JE, 2014, Management of whitefly-transmitted viruses in open-field production systems, *Adv Virus Res.*, **90**, 147-206.
- 180 Leach H, Wise JC and Isaacs R, 2017, Reduced ultraviolet light transmission increases insecticide longevity in protected culture raspberry production, *Chemosphere*, **189**, 454-465.
- 181 Lee H, Rahn T and Throop HL, 2012, An accounting of C-based trace gas release during abiotic plant litter degradation, *Glob. Change Biol.*, **18**, 1185-1195.
- 182 León-Chan RG, López-Meyer M, Osuna-Enciso T, Sañudo-Barajas JA, Heredia JB and León-Félix J, 2017, Low temperature and ultraviolet-B radiation affect chlorophyll content and induce the accumulation of UV-B-absorbing and antioxidant compounds in bell pepper (*Capsicum annuum*) plants, *Environ. Exp. Bot.*, **139**, 143-151.

- 183 Leone M, Keller MM, Cerrudo I and Ballaré CL, 2014, To grow or defend? Low red : far-red ratios reduce jasmonate sensitivity in *Arabidopsis* seedlings by promoting DELLA degradation and increasing JAZ10 stability, *New. Phytol.*, **204**, 355-367.
- 184 Leuchner M, Fabian P and Werner H, 2005, Spectral multichannel monitoring of radiation within a mature mixed forest, *Plant Biol. (Stuttg)*. **7**, 619-27.
- 185 Li N, Teranishi M, Yamaguchi H, Matsushita T, Watahiki MK, Tsuge T, Li SS and Hidema J, 2015, UV-B-induced CPD photolyase gene expression is regulated by UVR8-dependent and -independent pathways in *Arabidopsis*, *Plant Cell Physiol.*, **56**, 2014-2023.
- 186 Liang T, Mei S, Shi C, Yang Y, Peng Y, Ma L, Wang F, Li X, Huang X and Yin Y, 2018, UVR8 interacts with BES1 and BIM1 to regulate transcription and photomorphogenesis in *Arabidopsis*, *Dev. Cell*, **44**, 512-523. e5.
- 187 Liebmann B, Vera CS, Carvalho LMV, Camilloni IA, Hoerling MP, Allured D, Barros VR, Báez J and Bidegain M, 2004, An observed trend in central South American precipitation, *J. Climate*, **17**, 4357-4367.
- 188 Lim EP, Hendon HH, Arblaster JM, Delage F, Nguyen H, Min SK and Wheeler MC, 2016, The impact of the Southern Annular Mode on future changes in Southern Hemisphere rainfall, *Geophys. Res. Lett.*, **43**, 7160-7167.
- 189 Lin Y, Karlen SD, Ralph J and King JY, 2018, Short-term facilitation of microbial litter decomposition by ultraviolet radiation, *Sci. Tot. Environ.*, **615**, 838-848.
- 190 Lin Y, Scarlett RD and King JY, 2015, Effects of UV photodegradation on subsequent microbial decomposition of *Bromus diandrus* litter, *Plant Soil*, **395**, 263-271.
- 191 Lind O, Henze MJ, Kelber A and Osorio D, 2017, Coevolution of coloration and colour vision?, *Philos Trans R Soc Lond B Biol Sci*, **372**.
- 192 Linkosalo T and Lechowicz MJ, 2006, Twilight far-red treatment advances leaf bud burst of silver birch (*Betula pendula*), *Tree Physiol.*, **26**, 1249-1256.
- 193 Lipinski VM, Santos TG and Schuch AP, 2016, An UV-sensitive anuran species as an indicator of environmental quality of the Southern Atlantic Rainforest, *J Photochem Photobiol B*, **165**, 174-181.
- 194 Liu H, Cao X, Liu X, Xin R, Wang J, Gao J, Wu B, Gao L, Xu C, Zhang B, Grierson D and Chen K, 2017, UV-B irradiation differentially regulates terpene synthases and terpene content of peach, *Plant Cell Environ.*, **40**, 2261-2275.
- 195 Liu L, Gregan S, Winefield C and Jordan B, 2015, From UVR8 to flavonol synthase: UV-B-induced gene expression in Sauvignon blanc grape berry, *Plant Cell Environ.*, **38**, 905-919.
- 196 Llorens L, Ruben Badenes-Perez F, Julkunen-Tiitto R, Zidorn C, Fereres A and Jansen MAK, 2015, The role of UV-B radiation in plant sexual reproduction, *Perspect. Plant Ecol.*, **17**, 243-254.
- 197 Lomax BH, Fraser WT, Sephton MA, Callaghan TV, Self S, Harfoot M, Pyle JA, Wellman CH and Beerling DJ, 2008, Plant spore walls as a record of long-term changes in ultraviolet-B radiation, *Nat. Geosci.*, **1**, 592-596.

- 198 Londero JEL, Dos Santos CP, Segatto ALA and Passaglia Schuch A, 2017, Impacts of UVB radiation on food consumption of forest specialist tadpoles, *Ecotoxicol. Environ. Safety*, **143**, 12-18.
- 199 Lopez L, Stahle D, Villalba R, Torbenson M, Feng S and Cook E, 2017, Tree ring reconstructed rainfall over the southern Amazon Basin, *Geophys. Res. Lett.*, **44**, 7410-7418.
- 200 Lopez ML, Palancar GG and Toselli BM, 2012, Effects of stratocumulus, cumulus, and cirrus clouds on the UV-B diffuse to global ratio: Experimental and modeling results, *J. Quant. Spectrosc. Radiat. Transf.*, **113**, 461-469.
- 201 Luengo Escobar A, Magnum de Oliveira Silva F, Acevedo P, Nunes-Nesi A, Alberdi M and Reyes-Díaz M, 2017, Different levels of UV-B resistance in *Vaccinium corymbosum* cultivars reveal distinct backgrounds of phenylpropanoid metabolites, *Plant Physiol. Biochem.*, **118**, 541-550.
- 202 Ma Z, Yang W, Wu F and Tan B, 2017, Effects of light intensity on litter decomposition in a subtropical region, *Ecosphere*, **8**, e01770.
- 203 Maja MM, Kasurinen A, Holopainen T, Julkunen-Tiitto R and Holopainen JK, 2016, The effect of warming and enhanced ultraviolet radiation on gender-specific emissions of volatile organic compounds from European aspen, *Sci. Tot. Environ.*, **547**, 39-47.
- 204 Malenovský Z, Lucieer A, King Diana H, Turnbull Johanna D, Robinson Sharon A and Lecomte N, 2017, Unmanned aircraft system advances health mapping of fragile polar vegetation, *Methods Ecol. Evolut.*, **8**, 1842-1857.
- 205 Malenovský Z, Turnbull JD, Lucieer A and Robinson SA, 2015, Antarctic moss stress assessment based on chlorophyll content and leaf density retrieved from imaging spectroscopy data, *New. Phytol.*, **208**, 608-624.
- 206 Manatsa D, Morioka Y, Behera SK, Yamagata T and Matarira CH, 2013, Link between Antarctic ozone depletion and summer warming over southern Africa, *Nat. Geosci.*, **6**, 934-939.
- 207 Manatsa D, Mudavanhu C, Mushore TD and Mavhura E, 2016, Linking major shifts in East Africa 'short rains' to the Southern Annular Mode, *Int. J. Climatol.*, **36**, 1590-1599.
- 208 Manova V and Gruszka D, 2015, DNA damage and repair in plants – from models to crops, *Front. Plant. Sci.*, **6**.
- 209 Mao B, Wang Y, Zhao T-H, Tian R-R, Wang W and Ye J-S, 2017, Combined effects of elevated O₃ concentrations and enhanced UV-B radiation of the biometric and biochemical properties of soybean roots, *Front. Plant. Sci.*, **8**.
- 210 Mariani M and Fletcher M-S, 2016, The Southern Annular Mode determines interannual and centennial-scale fire activity in temperate southwest Tasmania, Australia, *Geophys. Res. Lett.*, **43**, 1702-1709.
- 211 Mariz-Ponte N, Mendes RJ, Sario S, Ferreira de Oliveira JMP, Melo P and Santos C, 2018, Tomato plants use non-enzymatic antioxidant pathways to cope with moderate UV-A/B irradiation: A contribution to the use of UV-A/B in horticulture, *J. Plant Physiol.*, **221**, 32-42.

- 212 Martin M, Meylan S, Haussy C, Decenci re B, Perret S and Le Galliard J-F, 2016, UV color determines the issue of conflicts but does not covary with individual quality in a lizard, *Behav. Ecol.*, **27**, 262-270.
- 213 Martin M, Meylan S, Perret S and Le Galliard J-F, 2015, UV coloration influences spatial dominance but not agonistic behaviors in male wall lizards, *Behav. Ecol. Sociobiol.*, **69**, 1483-1491.
- 214 Martin M, Th ry M, Rodgers G, Goven D, Sourice S, M ge P and Secondi J, 2016, UV wavelengths experienced during development affect larval newt visual sensitivity and predation efficiency, *Biol. Lett.*, **12**.
- 215 Martinez-Luscher J, Morales F, Delrot S, Sanchez-Diaz M, Gomes E, Aguirreolea J and Pascual I, 2015, Characterization of the adaptive response of grapevine (cv. Tempranillo) to UV-B radiation under water deficit conditions, *Plant Sci.*, **232**, 13-22.
- 216 Martinez-Luscher J, Morales F, Sanchez-Diaz M, Delrot S, Aguirreolea J, Gomes E and Pascual I, 2015, Climate change conditions (elevated CO₂ and temperature) and UV-B radiation affect grapevine (*Vitis vinifera* cv. Tempranillo) leaf carbon assimilation, altering fruit ripening rates, *Plant Sci.*, **236**, 168-176.
- 217 Martinez-Luscher J, Sanchez-Diaz M, Delrot S, Aguirreolea J, Pascual I and Gomes E, 2016, Ultraviolet-B alleviates the uncoupling effect of elevated CO₂ and increased temperature on grape berry (*Vitis vinifera* cv. Tempranillo) anthocyanin and sugar accumulation, *Aust. J. Grape Wine Res.*, **22**, 87-95.
- 218 Mart nez-L scher J, Torres N, Hilbert G, Richard T, S nchez-D  az M, Delrot S, Aguirreolea J, Pascual I and Gom s E, 2014, Ultraviolet-B radiation modifies the quantitative and qualitative profile of flavonoids and amino acids in grape berries, *Phytochem.*, **102**, 106-114.
- 219 Mayewski PA, Maasch KA and Dixon D, 2013, West Antarctica's sensitivity to natural and human-forced climate change over the Holocene, *J. Quat. Sci.*, **28**, 40-8.
- 220 Mazza CA and Ballar  CL, 2015, Photoreceptors UVR8 and phytochrome B cooperate to optimize plant growth and defense in patchy canopies, *New. Phytol.*, **207**, 4-9.
- 221 Mazza CA, Izaguirre MM, Zavala J, Scopel AL and Ballar  CL, 2002, Insect perception of ambient ultraviolet-B radiation, *Ecol. Lett.*, **5**, 722-726.
- 222 Mazza CA, Zavala J, Scopel AL and Ballar  CL, 1999, Perception of solar UVB radiation by phytophagous insects: Behavioral responses and ecosystem implications, *Proc. Nat. Acad. Sci. USA.*, **96**, 980-985.
- 223 McConnell JR, Aristarain AJ, Banta JR, Edwards PR and Sim  es JC, 2007, 20th-Century doubling in dust archived in an Antarctic Peninsula ice core parallels climate change and desertification in South America, *Proc. Nat. Acad. Sci. USA.*, **104**, 5743-5748.
- 224 McConnell JR, Burke A, Dunbar NW, K  hler P, Thomas JL, Arienzo MM, Chellman NJ, Maselli OJ, Sigl M, Adkins JF, Baggenstos D, Burkhart JF, Brook EJ, Buizert C, Cole-Dai J, Fudge TJ, Knorr G, Graf H-F, Grieman MM, Iverson N, McGwire KC, Mulvaney R, Paris G, Rhodes RH, Saltzman ES, Severinghaus JP, Steffensen JP,

- Taylor KC and Winckler G, 2017, Synchronous volcanic eruptions and abrupt climate change ≈ 17.7 ka plausibly linked by stratospheric ozone depletion, *Proc. Nat. Acad. Sci. USA.*, **114**, 10035.
- 225 McEnroe WD and Dronka K, 1966, Color vision in the adult female two-spotted spider mite, *Science*, **154**, 782.
- 226 McKenzie RL, Johnston PV, Smale D, Bodhaine BA and Madronich S, 2001, Altitude effects on UV spectral irradiance deduced from measurements at Lauder, New Zealand, and at Mauna Loa Observatory, Hawaii, *J. Geophys. Res. Atmos.*, **106**, 22845-22860.
- 227 Mejia-Giraldo JC, Henao-Zuluaga K, Gallardo C, Atehortua L and Puertas-Mejia MA, 2016, Novel *in vitro* antioxidant and photoprotection capacity of plants from high altitude ecosystems of Colombia, *Photochem. Photobiol.*, **92**, 150-7.
- 228 Mercado LM, Bellouin N, Sitch S, Boucher O, Huntingford C, Wild M and Cox PM, 2009, Impact of changes in diffuse radiation on the global land carbon sink, *Nature*, **458**, 1014.
- 229 Montzka SA, Dutton GS, Yu P, Ray E, Portmann RW, Daniel JS, Kuijpers L, Hall BD, Mondeel D, Siso C, Nance JD, Rigby M, Manning AJ, Hu L, Moore F, Miller BR and Elkins JW, 2018, An unexpected and persistent increase in global emissions of ozone-depleting CFC-11, *Nature*, **557**, 413-417.
- 230 Morales LO, Brosché M, Vainonen J, Jenkins GI, Wargent JJ, Sipari N, Strid A, Lindfors AV, Tegelberg R and Aphalo PJ, 2013, Multiple roles for UV RESISTANCE LOCUS8 in regulating gene expression and metabolite accumulation in *Arabidopsis* under solar ultraviolet radiation, *Plant Physiol.*, **161**, 744-759.
- 231 Moreno JE, Tao Y, Chory J and Ballaré CL, 2009, Ecological modulation of plant defense via phytochrome control of jasmonate sensitivity, *Proc. Nat. Acad. Sci. USA.*, **106**, 4935-40.
- 232 Morin X, Roy J, Sonié L and Chuine I, 2010, Changes in leaf phenology of three European oak species in response to experimental climate change, *New. Phytol.*, **186**, 900-910.
- 233 Mullen P and Pohland G, 2008, Studies on UV reflection in feathers of some 1000 bird species: are UV peaks in feathers correlated with violet-sensitive and ultraviolet-sensitive cones?, *Ibis*, **150**, 59-68.
- 234 Müller V, Albert A, Barbro Winkler J, Lankes C, Noga G and Hunsche M, 2013, Ecologically relevant UV-B dose combined with high PAR intensity distinctly affect plant growth and accumulation of secondary metabolites in leaves of *Centella asiatica* L. Urban, *J. Photochem. Photobiol. B.*, **127**, 161-169.
- 235 Munoz AA, Gonzalez-Reyes A, Lara A, Sauchyn D, Christie D, Puchi P, Urrutia-Jalabert R, Toledo-Guerrero I, Aguilera-Betti I, Mundo I, Sheppard PR, Stahle D, Villalba R, Szejner P, LeQuesne C and Vanstone J, 2016, Streamflow variability in the Chilean Temperate-Mediterranean climate transition (35 degrees S-42 degrees S) during the last 400 years inferred from tree-ring records, *Clim. Dyn.*, **47**, 4051-4066.
- 236 NASA, 2014, Ozone Hole Watch, National Aeronautics and Space Administration. Goddard Space Flight Center, <http://ozonewatch.gsfc.nasa.gov/>, accessed 2012.

- 237 Nenadis N, Llorens L, Koufogianni A, Diaz L, Font J, Abel Gonzalez J and Verdaguer D, 2015, Interactive effects of UV radiation and reduced precipitation on the seasonal leaf phenolic content/composition and the antioxidant activity of naturally growing *Arbutus unedo* plants, *J. Photochem. Photobiol. B.*, **153**, 435-444.
- 238 Neugart S, Fiol M, Schreiner M, Rohn S, Zrenner R, Kroh LW and Krumbein A, 2014, Interaction of moderate UV-B exposure and temperature on the formation of structurally different flavonol glycosides and hydroxycinnamic acid derivatives in kale (*Brassica oleracea* var. *sabellica*), *J. Agric. Food. Chem.*, **62**, 4054-4062.
- 239 Neugart S and Schreiner M, 2018, UVB and UVA as eustressors in horticultural and agricultural crops, *Scientia Horticult.*, **234**, 370-381.
- 240 Newsham KK and Robinson SA, 2009, Responses of plants in polar regions to UVB exposure: a meta-analysis, *Glob. Change Biol.*, **15**, 2574-2589.
- 241 Niang I, Ruppel O, Abdrabo M, Essel A, Lennard C, Padgham J and Urquhart P, 2014, Africa, in *IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* eds.: Field C, Baros V, Dokken D, Mach K, Mastrandrea M, Bilir T, Chatterjee M, Ebi K, Estrada Y, Genova R, Girma B, Kissel E, Levy A, MacCracken S, Mastrandrea P and White L, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199–1265.
- 242 Nile SH and Park SW, Edible berries: Bioactive components and their effect on human health, *Nutrition*, **30**, 134-144.
- 243 Nottebrock H, Schmid B, Mayer K, Devaux C, Esler Karen J, Böhning-Gaese K, Schleuning M, Pagel J and Schurr Frank M, 2016, Sugar landscapes and pollinator-mediated interactions in plant communities, *Ecography*, **40**, 1129-1138.
- 244 Novotná K, Klem K, Holub P, Rapantová B and Urban O, 2016, Evaluation of drought and UV radiation impacts on above-ground biomass of mountain grassland by spectral reflectance and thermal imaging techniques, *Beskydy*, **9**, 21-30.
- 245 Nybakken L, Hörkkä R and Julkunen-Tiitto R, 2012, Combined enhancements of temperature and UVB influence growth and phenolics in clones of the sexually dimorphic *Salix myrsinifolia*, *Physiol. Plant.*, **145**, 551-564.
- 246 O'Daniels ST, Kesler DC, Mihail JD, Webb EB and Werner SJ, 2017, Functional visual sensitivity to ultraviolet wavelengths in the Pileated Woodpecker (*Dryocopus pileatus*), and its influence on foraging substrate selection, *Physiol Behav*, **174**, 144-154.
- 247 Oliva M, Navarro F, Hrbacek F, Hernandez A, Nyvlt D, Pereira P, Ruiz-Fernandez J and Trigo R, 2017, Recent regional climate cooling on the Antarctic Peninsula and associated impacts on the cryosphere, *Sci Total Environ*, **580**, 210-223.
- 248 Oliveira FNM and Ambrizzi T, 2017, The effects of ENSO-types and SAM on the large-scale southern blockings, *Int. J. Climatol.*, **37**, 3067-3081.

- 249 Olsson LC, Veit M, Weissenböck G and Bornman JF, 1998, Differential flavonoid response to enhanced UV-B radiation in *Brassica napus*, *Phytochem.*, **49**, 1021-1028.
- 250 Palmieri L, Masuero D, Martinatti P, Baratto G, Martens S and Vrhovsek U, 2017, Genotype-by-environment effect on bioactive compounds in strawberry (*Fragaria x ananassa* Duch.), *J. Sci. Food. Agric.*, **97**, 4180-4189.
- 251 Pan X, Song Y-B, Liu G-F, Hu Y-K, Ye X-H, Cornwell WK, Prinzing A, Dong M and Cornelissen JHC, 2015, Functional traits drive the contribution of solar radiation to leaf litter decomposition among multiple arid-zone species, *Sci. Rep.*, **5**, 13217.
- 252 Pancotto VA, Sala OE, Cabello M, Lopez NI, Robson TM, Ballaré CL, Caldwell MM and Scopel AL, 2003, Solar UV-B decreases decomposition in herbaceous plant litter in Tierra del Fuego, Argentina: potential role of an altered decomposer community, *Glob. Change Biol.*, **9**, 1465-1474.
- 253 Parmesan C and Yohe G, 2003, A globally coherent fingerprint of climate change impacts across natural systems, *Nature*, **421**, 37.
- 254 Passaglia Schuch A, dos Santos MB, Mendes Lipinski V, Vaz Peres L, dos Santos CP, Zanini Cechin S, Jorge Schuch N, Kirsh Pinheiro D and da Silva Loreto EL, 2015, Identification of influential events concerning the Antarctic ozone hole over southern Brazil and the biological effects induced by UVB and UVA radiation in an endemic treefrog species, *Ecotoxicol. Environ. Safety*, **118**, 190-198.
- 255 Paul ND and Gwynn-Jones D, 2003, Ecological roles of solar UV radiation: towards an integrated approach, *TREE*, **18**, 48-55.
- 256 Pawson S, Steinbrecht W, [Lead Authors], Charlton-Perez AJ, Fujiwara M, A.Yu, Karpechko I, Petropavlovskikh, Urban J and Weber M, 2014, Update on Global Ozone: Past, Present, and Future, Chapter 2 in *Scientific Assessment of Ozone Depletion: 2014*, World Meteorological Organization Report No. 55, Geneva, Switzerland,
- 257 Pecl GT, Araújo MB, Bell JD, Blanchard J, Bonebrake TC, Chen I-C, Clark TD, Colwell RK, Danielsen F, Evengård B, Falconi L, Ferrier S, Frusher S, Garcia RA, Griffis RB, Hobday AJ, Janion-Scheepers C, Jarzyna MA, Jennings S, Lenoir J, Linnetved HI, Martin VY, McCormack PC, McDonald J, Mitchell NJ, Mustonen T, Pandolfi JM, Pettorelli N, Popova E, Robinson SA, Scheffers BR, Shaw JD, Sorte CJB, Strugnell JM, Sunday JM, Tuanmu M-N, Vergés A, Villanueva C, Wernberg T, Wapstra E and Williams SE, 2017, Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being, *Science*, **355**, eaai9214.
- 258 Perlwitz J, 2011, Tug of war on the jet stream, *Nat. Clim. Change*, **1**, 29-31.
- 259 Perovich DK, 2007, Light reflection and transmission by a temperate snow cover, *J. Glaciol.*, **53**, 201-210.
- 260 Petridis A, Döll S, Nichelmann L, Bilger W and Mock HP, 2016, *Arabidopsis thaliana* G2-G2-like flavonoid regulator and brassinosteroid enhanced expression1 are low-temperature regulators of flavonoid accumulation, *New. Phytol.*, **211**, 912-925.
- 261 Phoenix GK and Bjerke JW, 2016, Arctic browning: extreme events and trends reversing arctic greening, *Glob. Change Biol.*, **22**, 2960-2962.

- 262 Predick KI, Archer SR, Aguilon SM, Keller DA, Throop HL and Barnes PW, 2018, UV-B radiation and shrub canopy effects on surface litter decomposition in a shrub-invaded dry grassland, *J. Arid. Environ.*, **157**, 13-21.
- 263 Qi J, Zhang M, Lu C, Hettenhausen C, Tan Q, Cao G, Zhu X, Wu G and Wu J, 2018, Ultraviolet-B enhances the resistance of multiple plant species to lepidopteran insect herbivory through the jasmonic acid pathway, *Sci. Rep.*, **8**, 277.
- 264 Rafferty NE, 2017, Effects of global change on insect pollinators: Multiple drivers lead to novel communities, *Curr. Opin. Insect Sci.*, **23**, 22-27.
- 265 Randriamahefasoa TSM and Reason CJC, 2017, Interannual variability of rainfall characteristics over southwestern Madagascar, *Theoret. Appl. Climatol.*, **128**, 421-437.
- 266 Randriamanana TR, Lavola A and Julkunen-Tiitto R, 2015, Interactive effects of supplemental UV-B and temperature in European aspen seedlings: Implications for growth, leaf traits, phenolic defense and associated organisms, *Plant Physiol. Biochem.*, **93**, 84-93.
- 267 Rani S and Sud D, 2015, Role of enhanced solar radiation for degradation of triazophos pesticide in soil matrix, *Sol. Energy*, **120**, 494-504.
- 268 Rasines-Perea Z and Teissedre P-L, 2017, Grape polyphenols' effects in human cardiovascular diseases and diabetes, *Molecules*, **22**, 68.
- 269 Reddy KR, Patro H, Lokhande S, Bellaloui N and Gao W, 2016, Ultraviolet-B radiation alters soybean growth and seed quality, *Food Nutrit. Sci.*, **7**, 55.
- 270 Ritchie RJ, 2010, Modelling photosynthetic photon flux density and maximum potential gross photosynthesis, *Photosynthetica*, **48**, 596-609.
- 271 Rizzini L, Favory J-J, Cloix C, Faggionato D, O'Hara A, Kaiserli E, Baumeister R, Schaefer E, Nagy F, Jenkins GI and Ulm R, 2011, Perception of UV-B by the *Arabidopsis* UVR8 protein, *Science*, **332**, 103-106.
- 272 Robberecht R and Caldwell MM, 1978, Leaf epidermal transmittance of ultraviolet radiation and its implications for plant sensitivity to ultraviolet-radiation induced injury, *Oecologia*, **32**, 277-287.
- 273 Robinson SA and Erickson III DJ, 2015, Not just about sunburn--the ozone hole's profound effect on climate has significant implications for Southern Hemisphere ecosystems, *Glob. Change Biol.*, **21**, 515-527.
- 274 Robinson SA, King DH, Bramley-Alves J, Waterman MJ, Ashcroft MB, Wasley J, Turnbull JD, Miller RE, Ryan-Colton E, Benny T, Mullany K, Clarke LJ, Barry LA and Hua Q, 2018, Rapid change in East Antarctic terrestrial vegetation in response to regional drying, *Nat. Clim. Change*, **8**, 879-884.
- 275 Robson TM, Hartikainen SM and Aphalo PJ, 2015, How does solar ultraviolet-B radiation improve drought tolerance of silver birch (*Betula pendula* Roth.) seedlings?, *Plant Cell Environ.*, **38**, 953-967.
- 276 Robson TM, Pancotto VA, Flint SD, Ballaré CL, Sala OE, Scopel AL and Caldwell MM, 2003, Six years of solar UV-B manipulations affect growth of *Sphagnum* and vascular plants in a Tierra del Fuego peatland, *New Phytol.*, **160**, 379-389.

- 277 Royles J, Amesbury MJ, Convey P, Griffiths H, Hodgson DA, Leng MJ and Charman DJ, 2013, Plants and soil microbes respond to recent warming on the Antarctic Peninsula, *Curr. Biol.*, **23**, 1702-1706.
- 278 Rozema J, van Geel B, Bjorn LO, Lean J and Madronich S, 2002, Paleoclimate: Toward solving the UV puzzle, *Science*, **296**, 1621-1622.
- 279 Rutledge S, Campbell DI, Baldocchi D and Schipper LA, 2010, Photodegradation leads to increased carbon dioxide losses from terrestrial organic matter, *Glob. Change Biol.*, **16**, 3065-3074.
- 280 Sanchez-Lorenzo A, Enriquez-Alonso A, Calbo J, Gonzalez JA, Wild M, Folini D, Norris JR and Vicente-Serrano SM, 2017, Fewer clouds in the Mediterranean: consistency of observations and climate simulations, *Sci Rep*, **7**, 41475.
- 281 Savenstrand H, Brosche M and Strid A, 2004, Ultraviolet-B signalling: Arabidopsis brassinosteroid mutants are defective in UV-B regulated defence gene expression, *Plant Physiol Biochem*, **42**, 687-94.
- 282 Scheffers BR, De Meester L, Bridge TCL, Hoffmann AA, Pandolfi JM, Corlett RT, Butchart SHM, Pearce-Kelly P, Kovacs KM, Dudgeon D, Pacifici M, Rondinini C, Foden WB, Martin TG, Mora C, Bickford D and Watson JEM, 2016, The broad footprint of climate change from genes to biomes to people, *Science*, **354**, aaf7671.
- 283 Searles PS, Flint SD and Caldwell MM, 2001, A meta-analysis of plant field studies simulating stratospheric ozone depletion, *Oecologia*, **127**, 1-10.
- 284 Secondi J, Martin M, Goven D, Mege P, Sourice S and Thery M, 2017, Habitat-related variation in the plasticity of a UV-sensitive photoreceptor over a small spatial scale in the palmate newt, *J Evol Biol*, **30**, 1229-1235.
- 285 Seddon AWR, Jokerud M, Barth T, Birks HJB, Krüger LC, Vandvik V and Willis KJ, 2017, Improved quantification of UV-B absorbing compounds in *Pinus sylvestris* L. pollen grains using an internal standard methodology, *Rev. Palaeobot. Palynol.*, **247**, 97-104.
- 286 Seneviratne SI, Donat MG, Mueller B and Alexander LV, 2014, No pause in the increase of hot temperature extremes, *Nat. Clim. Change*, **4**, 161.
- 287 Seviour WJM, Gnanadesikan A and Waugh DW, 2016, The transient response of the Southern Ocean to stratospheric ozone depletion, *J. Climate*, **29**, 7383-7396.
- 288 Shoji T, 2007, Polyphenols as natural food pigments: Changes during food processing, *Am. J. Food Physiol.*, **2**, 570-581.
- 289 Singh SK, Reddy KR, Reddy VR and Gao W, 2014, Maize growth and developmental responses to temperature and ultraviolet-B radiation interaction, *Photosynthetica*, **52**, 262-271.
- 290 Sivadasan U, Randriamanana TR, Julkunen-Tiitto R and Nybakken L, 2015, The vegetative buds of *Salix myrsinifolia* are responsive to elevated UV-B and temperature, *Plant Physiol. Biochem.*, **93**, 66-73.
- 291 Skarbø K and VanderMolen K, 2016, Maize migration: key crop expands to higher altitudes under climate change in the Andes, *Clim. Dev.*, **8**, 245-255.

- 292 Smith KL and Polvani LM, 2017, Spatial patterns of recent Antarctic surface temperature trends and the importance of natural variability: lessons from multiple reconstructions and the CMIP5 models, *Clim. Dyn.*, **48**, 2653-2670.
- 293 Smith WK, Gao W, Steltzer H, Wallenstein MD and Tree R, 2010, Moisture availability influences the effect of ultraviolet-B radiation on leaf litter decomposition., *Glob. Change Biol.*, **16**, 484-495.
- 294 Solomon A and Polvani LM, 2016, Highly significant responses to anthropogenic forcings of the midlatitude jet in the Southern Hemisphere, *J. Climate*, **29**, 3463-3470.
- 295 Solomon A, Polvani LM, Smith KL and Abernathey RP, 2015, The impact of ozone depleting substances on the circulation, temperature, and salinity of the Southern Ocean: An attribution study with CESM1(WACCM), *Geophys. Res. Lett.*, **42**, 5547-5555.
- 296 Son SW, Purich A, Hendon Harry H, Kim BM and Polvani Lorenzo M, 2013, Improved seasonal forecast using ozone hole variability?, *Geophys. Res. Lett.*, **40**, 6231-6235.
- 297 Song JQ, Smart R, Wang H, Dambergs B, Sparrow A and Qian MC, 2015, Effect of grape bunch sunlight exposure and UV radiation on phenolics and volatile composition of *Vitis vinifera* L. cv. Pinot noir wine, *Food Chem.*, **173**, 424-431.
- 298 Soto-Vaca A, Gutierrez A, Losso JN, Xu Z and Finley JW, 2012, Evolution of phenolic compounds from color and flavor problems to health benefits, *J. Agric. Food. Chem.*, **60**, 6658-6677.
- 299 Steinbauer MJ, Grytnes J-A, Jurasinski G, Kulonen A, Lenoir J, Pauli H, Rixen C, Winkler M, Bardy-Durchhalter M, Barni E, Bjorkman AD, Breiner FT, Burg S, Czortek P, Dawes MA, Delimat A, Dullinger S, Erschbamer B, Felde VA, Fernández-Arberas O, Fossheim KF, Gómez-García D, Georges D, Grindrud ET, Haider S, Haugum SV, Henriksen H, Herreros MJ, Jaroszewicz B, Jaroszynska F, Kanka R, Kapfer J, Klanderud K, Kühn I, Lamprecht A, Matteodo M, di Cella UM, Normand S, Odland A, Olsen SL, Palacio S, Petey M, Piscová V, Sedlakova B, Steinbauer K, Stöckli V, Svenning J-C, Teppa G, Theurillat J-P, Vittoz P, Woodin SJ, Zimmermann NE and Wipf S, 2018, Accelerated increase in plant species richness on mountain summits is linked to warming, *Nature*, **556**, 231-234.
- 300 Stratmann JW, Stelmach BA, Weller EW and Ryan CA, 2000, UVB/UVA radiation activates a 48 kDa myelin basic protein kinase and potentiates wound signaling in tomato leaves, *Photochem. Photobiol.*, **71**, 116-123.
- 301 Suchar VA and Robberecht R, 2017, Integration and scaling of UV-B radiation effects on plants: the relative sensitivity of growth forms and interspecies interactions, *J. Plant Ecol.*, **11**, 656-670.
- 302 Suklje K, Antalick G, Coetzee Z, Schmidtke LM, Cesnik HB, Brandt J, du Toit WJ, Lisjak K and Deloire A, 2014, Effect of leaf removal and ultraviolet radiation on the composition and sensory perception of *Vitis vinifera* L. cv. Sauvignon Blanc wine, *Aust. J. Grape Wine Res.*, **20**, 223-233.

- 303 Sullivan JH, Gitz DC, Liu-Gitz L, Xu CP, Gao W and Slusser J, 2007, Coupling short-term changes in ambient UV-B levels with induction of UV-screening compounds, *Photochem. Photobiol.*, **83**, 863-870.
- 304 Sun M, Su T, Zhang SB, Li SF, Anberree-Lebreton J and Zhou ZK, 2016, Variations in leaf morphological traits of *Quercus guyavifolia* (Fagaceae) were mainly influenced by water and ultraviolet irradiation at high elevations on the Qinghai-Tibet Plateau, China, *Int. J. Agric. Biol.*, **18**, 266-273.
- 305 Tang J, Körner C, Muraoka H, Piao S, Shen M, Thackeray Stephen J and Yang X, 2016, Emerging opportunities and challenges in phenology: a review, *Ecosphere*, **7**, e01436.
- 306 Tao L, Hu Y and Liu J, 2016, Anthropogenic forcing on the Hadley circulation in CMIP5 simulations, *Clim. Dyn.*, **46**, 3337-3350.
- 307 Thackeray SJ, Henrys PA, Hemming D, Bell JR, Botham MS, Burthe S, Helaouet P, Johns DG, Jones ID, Leech DI, Mackay EB, Massimino D, Atkinson S, Bacon PJ, Brereton TM, Carvalho L, Clutton-Brock TH, Duck C, Edwards M, Elliott JM, Hall SJ, Harrington R, Pearce-Higgins JW, Hoyer TT, Kruuk LE, Pemberton JM, Sparks TH, Thompson PM, White I, Winfield IJ and Wanless S, 2016, Phenological sensitivity to climate across taxa and trophic levels, *Nature*, **535**, 241-5.
- 308 Thomas BC, 2017, Photobiological effects at Earth's surface following a 50 pc supernova, *Astrobiol.*, **18**, 481-490.
- 309 Thomas BC, Goracke BD and Dalton SM, 2016, Atmospheric constituents and surface-level UVB: Implications for a paleoaltimetry proxy and attempts to reconstruct UV exposure during volcanic episodes, *Earth Planet Sci. Lett.*, **453**, 141-151.
- 310 Tomás-Barberán FA and Espín Juan C, 2001, Phenolic compounds and related enzymes as determinants of quality in fruits and vegetables, *J. Sci. Food. Agric.*, **81**, 853-876.
- 311 Tomotani BM, Jeugd H, Gienapp P, Hera I, Pilzecker J, Teichmann C and Visser ME, 2017, Climate change leads to differential shifts in the timing of annual cycle stages in a migratory bird, *Glob. Change Biol.*, **24**, 823-835.
- 312 Tossi V, Lamattina L, Jenkins GI and Cassia RO, 2014, Ultraviolet-B-induced stomatal closure in *Arabidopsis* is regulated by the UV RESISTANCE LOCUS8 photoreceptor in a nitric oxide-dependent mechanism, *Plant Physiol.*, **164**, 2220-2230.
- 313 Trest MT, Will-Wolf S, Keuler R, Shay N, Hill K, Studer A, Muench A, Alexander Z, Adams A, Dittberner L, Feehan M, Lee H, Galleguillos-Katz N, Zedler JB, Graham L and Arancibia-Avila P, 2015, Potential impacts of UV exposure on lichen communities: a pilot study of *Nothofagus dombeyi* trunks in southernmost Chile, *Ecosys. Health Sustain.*, **1**, art14.
- 314 Tripathi R and Agrawal SB, 2016, Effect of supplemental UV-B on yield, seed quality, oil content and fatty acid composition of *Brassica campestris* L. under natural field conditions, *Qual. Assur. Safe. Crops Foods*, **8**, 11-20.

- 315 Turner J, Lu H, White I, King JC, Phillips T, Hosking JS, Bracegirdle TJ, Marshall GJ, Mulvaney R and Deb P, 2016, Absence of 21st century warming on Antarctic Peninsula consistent with natural variability, *Nature*, **535**, 411-415.
- 316 Umeno A, Horie M, Murotomi K, Nakajima Y and Yoshida Y, 2016, Antioxidative and antidiabetic effects of natural polyphenols and isoflavones, *Molecules*, **21**, 708.
- 317 Urban O, Klem K, Ač A, Havráňková K, Holišová P, Navrátil M, Zitová M, Kozlová K, Pokorný R, Šprtová M, Tomášková I, Špunda V and Grace J, 2012, Impact of clear and cloudy sky conditions on the vertical distribution of photosynthetic CO₂ uptake within a spruce canopy, *Funct. Ecol.*, **26**, 46-55.
- 318 Urban O, Košovancová M, Marek MV and Lichtenthaler HK, 2007, Induction of photosynthesis and importance of limitations during the induction phase in sun and shade leaves of five ecologically contrasting tree species from the temperate zone, *Tree Physiol.*, **27**, 1207-1215.
- 319 USGCRP, 2017, Climate Science Special Report: Fourth National Climate Assessment, Volume I, U.S. Global Change Research Program Report No., Washington, DC, USA, p. 470
- 320 Vera CS and Díaz L, 2014, Anthropogenic influence on summer precipitation trends over South America in CMIP5 models, *Int. J. Climatol.*, **35**, 3172-3177.
- 321 Verdaguer D, Díaz-Guerra L, Font J, González JA and Llorens L, 2018, Contrasting seasonal morphological and physio-biochemical responses to UV radiation and reduced rainfall of two mature naturally growing Mediterranean shrubs in the context of climate change, *Environ. Exp. Bot.*, **147**, 189-201.
- 322 Verdaguer D, Jansen MAK, Llorens L, Morales LO and Neugart S, 2017, UV-A radiation effects on higher plants: Exploring the known unknown, *Plant Sci.*, **255**, 72-81.
- 323 Vilfan N, Van Der Tol C, Yang P, Wyber R, Malenovsky Z, Robinson SA and Verhoef W, 2018, Extending Fluspect to simulate xanthophyll driven leaf reflectance dynamics *Rem. Sens. Environ.*, **211**, 345-356.
- 324 Vilfan N, van der Tol C, Yang P, Wyber R, Malenovsky Z and Robinson SA, 2018, A model for leaf dynamic xanthophyll reflectance, *Rem. Sens. Environ.*, **In Review**.
- 325 Villalba R, Lara A, Masiokas MH, Urrutia R, Luckman BH, Marshall GJ, Mundo IA, Christie DA, Cook ER, Neukom R, Allen K, Fenwick P, Boninsegna JA, Srur AM, Morales MS, Araneo D, Palmer JG, Cuq E, Aravena JC, Holz A and LeQuesne C, 2012, Unusual Southern Hemisphere tree growth patterns induced by changes in the Southern Annular Mode, *Nat. Geosci.*, **5**, 793-798.
- 326 Virjamo V, Sutinen S and Julkunen-Tiitto R, 2014, Combined effect of elevated UVB, elevated temperature and fertilization on growth, needle structure and phytochemistry of young Norway spruce (*Picea abies*) seedlings, *Glob. Change Biol.*, **20**, 2252-2260.
- 327 Visscher H, Looy CV, Collinson ME, Brinkhuis H, van Konijnenburg-van Cittert JHA, Kürschner WM and Sephton MA, 2004, Environmental mutagenesis during the end-Permian ecological crisis, *Proc. Nat. Acad. Sci. USA.*, **101**, 12952.

- 328 Wang H, Gui M, Tian X, Xin X, Wang T and li J, 2017, Effects of UV-B on vitamin C, phenolics, flavonoids and their related enzyme activities in mung bean sprouts (*Vigna radiata*), *Int. J. Food Sci. Technol.*, **52**, 827-833.
- 329 Wang H, Ma XC, Zhang L, Siemann E and Zou JW, 2016, UV-B has larger negative impacts on invasive populations of *Triadica sebifera* but ozone impacts do not vary, *J. Plant Ecol.*, **9**, 61-68.
- 330 Wang J, Liu L, Wang X, Yang S, Zhang B, Li P, Qiao C, Deng M and Liu W, 2017, High night-time humidity and dissolved organic carbon content support rapid decomposition of standing litter in a semi-arid landscape, *Funct. Ecol.*, **31**, 1659-1668.
- 331 Wang J, Yang S, Zhang B, Liu W, Deng M, Chen S and Liu L, 2017, Temporal dynamics of ultraviolet radiation impacts on litter decomposition in a semi-arid ecosystem, *Plant Soil*, **419**, 71-81.
- 332 Wang Q-W, Nagano S, Ozaki H, Morinaga S-I, Hidema J and Hikosaka K, 2016, Functional differentiation in UV-B-induced DNA damage and growth inhibition between highland and lowland ecotypes of two *Arabidopsis* species, *Environ. Exp. Bot.*, **131**, 110-119.
- 333 Wang QW, Kamiyama C, Hidema J and Hikosaka K, 2016, Ultraviolet-B-induced DNA damage and ultraviolet-B tolerance mechanisms in species with different functional groups coexisting in subalpine moorlands, *Oecologia*, **181**, 1069-1082.
- 334 Wargent JJ, 2017, Turning UV-B Photobiology into Commercial Reality, in *The Role of UV-B Radiation in Plant Growth and Development* ed.: Jordan BR, CABI Press, Oxford, UK, pp. 163-176.
- 335 Wargent JJ and Jordan BR, 2013, From ozone depletion to agriculture: understanding the role of UV radiation in sustainable crop production, *New Phytol.*, **197**, 1058-1076.
- 336 Wargent JJ, Nelson BCW, McGhie TK and Barnes PW, 2015, Acclimation to UV-B radiation and visible light in *Lactuca sativa* involves up-regulation of photosynthetic performance and orchestration of metabolome-wide responses, *Plant Cell Environ.*, **38**, 929-940.
- 337 Waterman MJ, Nugraha AS, Hendra R, Ball GE, Robinson SA and Keller PA, 2017, Antarctic moss biflavonoids show high antioxidant and ultraviolet-screening activity, *J. Nat. Prod.*, **80**, 2224-2231.
- 338 Waugh DW, Garfinkel CI and Polvani LM, 2015, Drivers of the recent tropical expansion in the Southern Hemisphere: Changing SSTs or ozone depletion?, *J. Climate*, **28**, 6581-6586.
- 339 Way DA and Montgomery RA, 2015, Photoperiod constraints on tree phenology, performance and migration in a warming world, *Plant Cell Environ.*, **38**, 1725-1736.
- 340 Weber J, Halsall CJ, Wargent JJ and Paul ND, 2009, The aqueous photodegradation of fenitrothion under various agricultural plastics: Implications for pesticide longevity in agricultural 'micro-environments', *Chemosphere*, **76**, 147-150.

- 341 Wightman JD and Heuberger RA, 2015, Effect of grape and other berries on cardiovascular health, *J. Sci. Food. Agric.*, **95**, 1584-1597.
- 342 Wijewardana C, Henry WB, Gao W and Reddy KR, 2016, Interactive effects on CO₂, drought, and ultraviolet-B radiation on maize growth and development, *J. Photochem. Photobiol. B.*, **160**, 198-209.
- 343 Williamson CE, Zepp RG, Lucas RM, Madronich S, Austin AT, Ballaré CL, Norval M, Sulzberger B, Bais AF, McKenzie RL, Robinson SA, Häder D-P, Paul ND and Bornman JF, 2014, Solar ultraviolet radiation in a changing climate, *Nat. Clim. Change*, **4**, 434-441.
- 344 Willis KJ, Feurdean A, Birks HJB, Bjune AE, Breman E, Broekman R, Grytnes JA, New M, Singarayer JS and Rozema J, 2011, Quantification of UV-B flux through time using UV-B-absorbing compounds contained in fossil *Pinus* sporopollenin, *New. Phytol.*, **192**, 553-560.
- 345 WMO, 2014, Assessment for Decision-Makers: Scientific Assessment of Ozone Depletion: 2014, Report No., Geneva, Switzerland,
- 346 WMO, 2018, Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project-Report No. 55, Report No., Geneva, Switzerland,
- 347 Wolf A, Zimmerman NB, Anderegg WRL, Busby PE and Christensen J, 2016, Altitudinal shifts of the native and introduced flora of California in the context of 20th-century warming, *Glob. Ecol. Biogeog.*, **25**, 418-429.
- 348 Wu C, Zhang Z, Wang H, Li C, Mo Q and Liu Y, 2018, Photodegradation accelerates coarse woody debris decomposition in subtropical Chinese forests, *Forest Ecol. Manag.*, **409**, 225-232.
- 349 Wu G, Bornman JF, Bennett SJ, Clarke MW, Fang Z and Johnson SK, 2017, Individual polyphenolic profiles and antioxidant activity in sorghum grains are influenced by very low and high solar UV radiation and genotype, *J.Cereal Sci.*, **77**, 17-23.
- 350 Wu G, Johnson S, K., Bornman J, F., Bennett S, Singh V and Fang Z, 2016, Effect of genotype and growth temperature on sorghum grain physical characteristics, polyphenol content, and antioxidant activity, *Cereal. Chem.*, **93**, 419-425.
- 351 Wu G, Johnson SK, Bornman JF, Bennett SJ, Clarke MW, Singh V and Fang Z, 2016, Growth temperature and genotype both play important roles in sorghum grain phenolic composition, *Sci. Rep.*, **6**, 21835.
- 352 Wu Y and Polvani LM, 2017, Recent trends in extreme precipitation and temperature over southeastern South America: The dominant role of stratospheric ozone depletion in the CESM large ensemble, *J. Climate*, **30**, 6433-6441.
- 353 Wyber R, Malenovský Z, Ashcroft M, Osmond B and Robinson S, 2017, Do daily and seasonal trends in leaf solar induced fluorescence reflect changes in photosynthesis, growth or light exposure?, *Remote Sensing*, **9**.
- 354 Yang C, Wang J and Liang W, 2016, Blocking of ultraviolet reflectance on bird eggs reduces nest predation by aerial predators, *J. Ornithol.*, **157**, 43-47.

- 355 Yang Y, Niu K, Hu Z, Niklas KJ and Sun S, 2018, Linking species performance to community structure as affected by UV-B radiation: an attenuation experiment, *J. Plant Ecol.*, **11**, 286-296.
- 356 Yin R and Ulm R, 2017, How plants cope with UV-B: from perception to response, *Curr. Opin. Plant Biol.*, **37**, 42-48.
- 357 Yu Z, Beilman DW and Loisel J, 2016, Transformations of landscape and peat-forming ecosystems in response to late Holocene climate change in the western Antarctic Peninsula, *Geophys. Res. Lett.*, **43**, 7186-7195.
- 358 Zavala JA, Mazza CA, Dillon FM, Chludil HD and Ballaré CL, 2015, Soybean resistance to stink bugs (*Nezara viridula* and *Piezodorus guildinii*) increases with exposure to solar UV-B radiation and correlates with isoflavonoid content in pods under field conditions, *Plant Cell Environ.*, **38**, 920-928.
- 359 Zhang J, Tian W, Chipperfield MP, Xie F and Huang J, 2016, Persistent shift of the Arctic polar vortex towards the Eurasian continent in recent decades, *Nat. Clim. Change*, **6**, 1094.
- 360 Zhang Y, Feng L, Jiang H, Zhang Y and Zhang S, 2017, Different proteome profiles between male and female *Populus cathayana* exposed to UV-B radiation, *Front. Plant. Sci.*, **8**, 320.
- 361 Zhou Z, Schenke D, Miao Y and Cai D, 2017, Investigation of the crosstalk between the flg22 and the UV-B-induced flavonol pathway in *Arabidopsis thaliana* seedlings, *Plant Cell Environ.*, **40**, 453-458.
- 362 Zohner CM, Benito BM, Svenning J-C and Renner SS, 2016, Day length unlikely to constrain climate-driven shifts in leaf-out times of northern woody plants, *Nat. Clim. Change*, **6**, 1120.