Impacts of Climate Change on Plant Mycobiome

Abdelghafar M. Abu-Elsaoud and Walaa I. Saadeldin

1 Introduction

There is widespread agreement that climate change is a serious threat to the environment and one of the most pressing social issues of the century. More atmospheric carbon dioxide (CO_2) and, by extension, increased ultraviolet radiation (UVR) reaching Earth's surface owing to both rising temperatures and ozone depletion are two of the many phenomena associated to global climate change that have their roots in industrialization (Madronich et al. 1998). These climatic shifts may have both direct and indirect effects on organisms, altering their phenology and physiology (Beaugrand et al. 2003; Cloern et al. 2005) and impacting environmental parameters that regulate mortality and growth (Beardall et al. 2009). There is a chance that this might change the species' range, the composition of communities, and the ecosystem's ability to operate (Beaugrand et al. 2002).

The effects of ultraviolet radiation (UVR) on plants and fungi are not only dependent on the UVR's intensity and spectrum content, but also on the interaction of UVR exposure with other environmental factors such as nutrients (Marcoval et al. 2007), light acclimation history (van de Poll et al. 2006), and temperature (Villafañe

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Y. M. Rashad et al. (eds.), *Plant Mycobiome*,
https://doi.org/10.1007/978-3-031-28307-9_18

et al. 2008). (Boyd et al. 2010). Biological processes including nutrition uptake, growth, species composition, and toxin generation might all be negatively impacted by UVR. Evidence from many studies (Beardall et al. 2009; Fu et al. 2012; Hogue et al. 2005) supports this notion. The community structure of phytoplankton might shift as a result of this since various species/groups react differently to UVR. As a result of affecting both the dark and light responses of photosynthesis at photosystem II, namely the enzyme RuBisCO (Vincent and Neale 2000), exposure to UVR can reduce photosynthetic rates. Significant UVR-induced damage on nucleic acids has also been observed (Boelen et al. 1999; Buma et al. 1996), leading to nucleotide damage and the production of photoproducts (Görner 1994). These photoproducts, such as pyrimidine dimers, can induce mutations and decrease the amount of free RNA polymerase, which affects transcription (Britt 1996). UVR exposure has been linked to an increase in reactive oxygen species (He and Häder 2002), which may damage macromolecules including lipids, DNA, and proteins, leading to oxidative damage and possibly even cell death.

The rise in atmospheric carbon dioxide concentrations since the start of the Industrial Revolution has had a significant impact on global warming. The increase in atmospheric CO_2 from 280 parts per million (before the start of the Industrial Revolution) to the present 410 parts per million is roughly proportional to the increase in average global temperature of about 1 °C since 1880. (Ciais et al. 2014). As long as CO_2 concentrations are on the increase, the Earth will continue to warm, but the extent to which this happens will rely on political will and human ability to limit carbon emissions as quickly as feasible. Therefore, increasing temperatures will lead to different climatic conditions in many places, which will affect the way species operate and their current geographic ranges. By taking in some of the carbon dioxide (CO_2) emitted into the air from burning fossil fuels, terrestrial plants have played an important role in mitigating climate change. Ciais et al. (2014) found that plants now absorb 30% of annual CO_2 emissions, hence slowing the pace at which the planet is warming. However, plants are adaptive, and some of them may adjust their optimal development temperature based on external conditions (see below). Because forests are responsible for a sizable proportion of global terrestrial production, knowing how they will respond to climate change is crucial for foreseeing the future. In order to assess how trees in a forest will react to rising temperatures, it is important to measure any potential changes in tree physiology. One of the major gaps in our knowledge of the carbon cycle and our capacity to forecast future increases in atmospheric CO_2 concentrations is how temperature influences the physiological changes of forest trees (Mercado et al. 2018). Since the greatest fluxes of carbon intake and loss occur during photosynthesis and respiration, respectively, the capacity of a species to physically modify its plant metabolism is a first line of defence for how they would adapt to rising temperatures. The topics of this chapter include global warming (temperature), UV radiation, and carbon dioxide emissions.

2 Effect of Climate Change on Plants and Mycobiota

2.1 Ultraviolet Radiations

2.1.1 Nature of Light

Light is an essential source of energy for virtually all organisms on Earth. Many different kinds of organisms are able to absorb and use the energy from light. Autotrophs and plants, for instance, are able to achieve this via photosynthesis. However, light has many other functions than providing energy for biological reactions. Its quality (the ratio of photons at different wavelengths), intensity (energy flux), and relationships to other environmental characteristics all reveal information about the condition of the environment right now. (Jones et al. 2013).

Relativity and quantum physics, the two dominant theories of the twentieth century, both focus on the behaviour of as light travels through space as well as interacts with matter. The study of this phenomenon is also crucial to our knowledge of how organisms behave and operate (Björn 2015).

Photomorphogenesis is described as an organism's developmental reaction to information in light, such as the amount of light, the quality of light in terms of wavelengths present, the direction of light, or the length of night and day and (photoperiod). Photoreceptors are molecules within cells that take in light and trigger a series of reactions in the organism when exposed to it (Jones et al. 2013). *Photostimulators* are a specific kind of light utilised in the process of *photostimulation*, which is the use of light to stimulate biological processes.

2.2 Electromagnetic Spectrum

For all forms of energy production that do not involve nuclear fission, the Sun is indispensable. Energy from the sun is the result of nuclear fusion, and each year the Earth absorbs around 5.62 × 1024 joules of solar radiation through its atmosphere, seas, and landmasses; of this amount, photosynthesis is responsible for capturing 3.16 × 1021 joules (Table 1). The electromagnetic spectrum includes not only visible light but also - and X-rays, and all the way to radio waves at the other end. Light is both a particle and a wave at the same time. As a simplified metaphor, think of it as waves made up of discrete packets of energy, or quanta. A photon is the quantization of light's energy. Lambda (λ), the Greek letter that represents wavelength, is often written in nanometers when referring to visible light (nm). Radiation with wavelengths between around 380 nm (violet) and 760 nm (far red) is known as the visible spectrum (Fig. 1). Equation 14.1 expresses the relationship between frequency (ν, Greek letter nu; units = s^{-1}), speed of light (c, units = m s^{-1}), and wavelength (in meters). There are two primary characteristics of light. Light has both particle and wave qualities, and they can be clearly seen in an adjusted version of Young's double-slit experiment (Jones 2013).

Table 1 The fate of solar energy reaching Earth (Jones 2013)

Global solar power balance	Amount in terawatts[a]
Solar power input[b]	178,000
Reflected to space immediately	53,000
Absorbed and then reflected as heat	82,000
Used to evaporate water	40,000
Captured by photosynthesis (net primary productivity)[c]	100
Total power used by human society	
In 2005	13
Projected use in 2100	46
Total used for food	0.6

[a] Power is measured in watts, and a watt is equal to one joule every second. Terawatts are measured in units of power equivalent to 1012 joules second^{-1}, or 1012 watts

[b] Solar energy input is 5.621012 terawatts (5.621024 joules)

[c] Photosynthetic organisms are responsible for harvesting an average of 3.16 × 109 terawatts (3.16 × 1021 joules) of solar energy every year

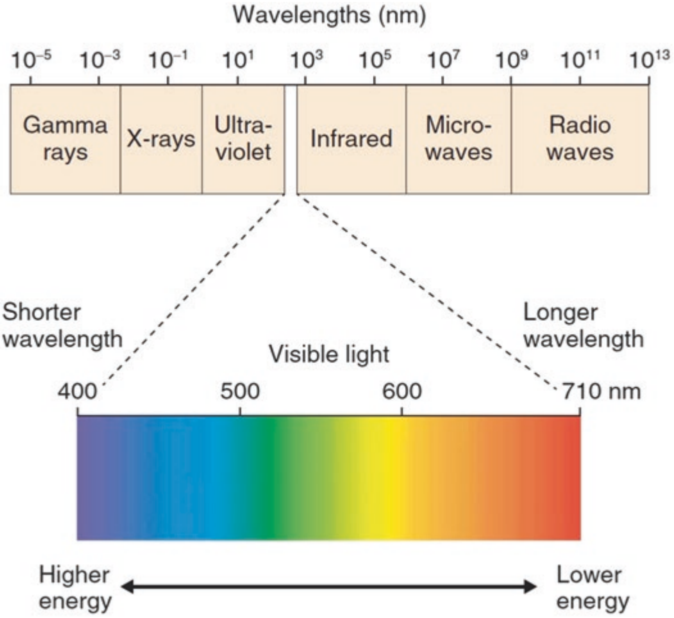

Fig. 1 The visible portion of the electromagnetic spectrum, from 400 to 710 nm, enlarged to display colour. The blue end of the spectrum (380 nm) and the red end of the spectrum (760 nm) are not the absolute limiting factors for human perceptual abilities. Keep in mind that the units of energy are J mol^{-1} (Jones 2013)

Equation 1 Relationship between light speed, frequency & wavelength

$$c = \upsilon\lambda$$

Equation 2 Energy as a function of electromagnetic radiation wavelength or frequency:

$$E = hc / \lambda$$

Where c = speed of light (approximately 300×10^{6} m s^{-1}) and h = Planck's constant (4.14×10^{-15} eV.s).

2.3 *Photobiology: Interaction of Light with Living Organisms*

Photobiology is the study of how various wavelengths of light influence living organisms. Photoreceptors are light-absorbing molecules that trigger a series of reactions in living things when they detect light (Jones et al. 2013). Photostimulators are a specific kind of light utilised in the process of photostimulation, which is the use of light to stimulate biological processes. Photoreceptor molecules detect light and transmit that information to the cell so that the body may respond to changes in its environment.

Rhodopsin is found in the eyes of humans and other animals and functions as a photoreceptor. Photoreceptors are found in a wide variety of plant and microbial species. Phytochromes, cryptochromes, and phototropins are all examples of photosynthetic pigments. There is a unique spectrum of light that is taken in by each type of photoreceptor. Absorption of light by a photoreceptor causes a variety of reactions depending on the wavelength of the light. An action spectrum is the result of plotting the magnitude of a certain physiological reaction against the wavelengths that elicit that response. The photoreceptor responsible for a given reaction can be determined by measuring the spectrum of the associated action potential.

UV light with shorter wavelengths than the visible and infrared ranges display a greater number of quantum characteristics. We arbitrarily divide ultraviolet light into three bands, each with distinct biological consequences. Since it carries the least amount of energy, UV-A light is the least dangerous and most frequent kind of UV radiation. The ultraviolet-a (UV-A) spectrum of light is commonly referred to as "black light" because of its reputation for inducing visible light emission from fluorescent materials. UV-A lamps, the kind used in tanning salons and phototherapy, are the most common (Fig. 2).

Since UV-B has enough energy to destroy living tissues yet is not completely absorbed by the atmosphere, it is the most dangerous kind of UV radiation. Overexposure to UV-B rays has been linked to skin cancer. Given that the atmosphere blocks most of the UV-B radiation from space, even a little change in the

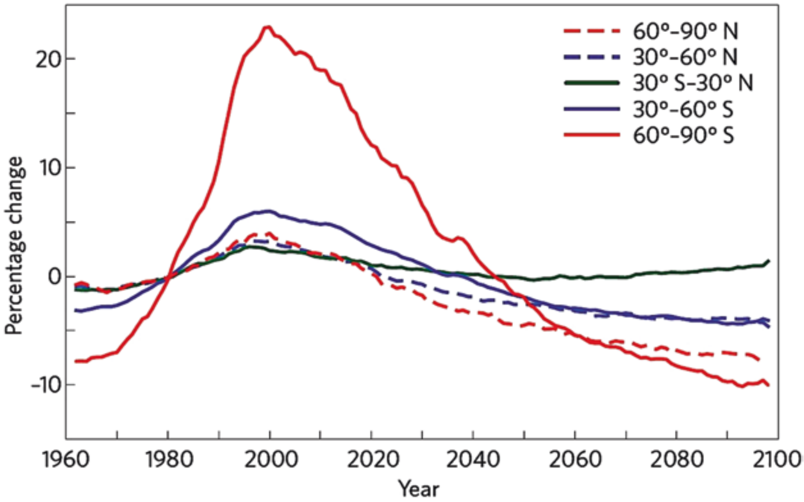

Fig. 2 Annual mean erythemal (skin-burning) clear-sky UV-B radiation at the Earth's surface, observed (before 2010) and anticipated (after 2010) compared to 1980 for different latitude bands (Bais et al. 2015; McKenzie et al. 2011; Williamson et al. 2014)

ozone layer might significantly increase the risk of skin cancer. While the sun's ultraviolet radiation (UV) is essential for life on Earth, it has the potential to damage living as well as non-living organisms. Conventionally, UV light has been separated into three wavelength bands: UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (200 nm) (100–280 nm). Potentially harmful ultraviolet (UV)-C radiation is blocked entirely by Earth's atmosphere before it reaches the planet's surface. Stratospheric ozone absorbs the most harmful short wavelength UV-B radiation, protecting Earth's surface from it. The majority of the sun's ultraviolet (UV) light reaching the ground is UV-A, which is mostly unimpeded by the Earth's atmosphere. UV-A radiation is mutagenic and suppresses the immune system in humans, but it also has essential impacts on tropospheric chemistry, air quality, aquatic and soil processes, and is typically less hazardous than UV-B radiation (Damian et al. 2011). Insect pests and harmful bacteria can be effectively repressed by plants' natural defence mechanisms, and solar UV light, especially UV-B, can be a positive regulator of these mechanisms (Williamson et al. 2014). Microorganisms can be affected positively or negatively by UV light, with UV-A and UV-B having the most dramatic impacts (Abu-Elsaoud and Abdel-Azeem 2020).

In an in vitro experiment, we determined how exposure to higher UV radiation levels, particularly UVA + UVB, affected certain aeromycobiota from the Ismailia region in Egypt (unpublished data). *Paecilomyces* sp. and *Drechslera* sp. were the two kinds of fungi examined. While both *Drechslera* sp. and *Paecilomyces* sp. showed an effect of UV-B and UV-A on biochemical consequences and conidial structure (size), UV-absorbing compound levels were found to be much higher in *Paecilomyces* following irradiation with both wavelengths compared to the control group. Mycosporine-like amino acids (MAAs) were found in increased quantities (Abu-Elsaoud and Abdel-Azeem 2020). Table 2 Summarized selected studies on the effect of climate change in terms of Electromagnetic spectrum on microorganisms especially fungi (Figs. 3 and 4).

The majority of filamentous fungi finish their asexual life cycle by forming specialised structures known as conidia. They are critical to the proliferation of fungi as well as the survival of their habitats. They also play a role in pathogenic species identification and infection. Solar radiation can have a variety of effects on conidial production, survival, dispersal, germination, pathogenicity, and virulence, some of

Table 2 Some selected studies Effect of climate change in terms of Electromagnetic spectrum on microorganisms especially fungi

EM radiation	Wavelength (λ; nm)	Subject	Microorganism	Reference
UV-B	280–320	Growth, pigmentation, and spore generation in the phytopathogenic fungus Alternaria solani in response to ultraviolet B light	*Alternaria solani*	Fourtouni et al. (1998)
UV-B	280–320	Effect of UV-B irradiation on the antioxidant activity and content of the medicinal Caterpillar fungus, Cordyceps militaris (ascomycetes)	*Cordyceps militaris*	Huang et al. (2015)
		Serpula himantioides cultures exposed to UV-B radiation accumulate more xerocomic acid, which is found in the cell wall	*Serpula himantioides*	Torres et al. (2019)
		Physiological and molecular effects of environmental UV radiation on fungal conidia	*Magnaporthe grisea*, *Alternaria alternata*, *Colletotrichum lagenarium*, *Cochliobolus heterostrophus*, and *Aspergillus* spp.	Braga et al. (2015)
UV-A + UV-B	320–400	Conidial structure has been altered	*Fungi*: *Drechslera* sp. *Paecilomyces* sp.	Abu-Elsaoud and Abdel-Azeem (2020)
	280–320	UV-absorbing chemicals have been increased		
		Mycosporine-like-amino acids have increased (MAAs)		
He-Ne laser and UV		Endo-polysaccharide synthesis and antioxidant activity	*Phellinus igniarius*	Zhang et al. (2016)

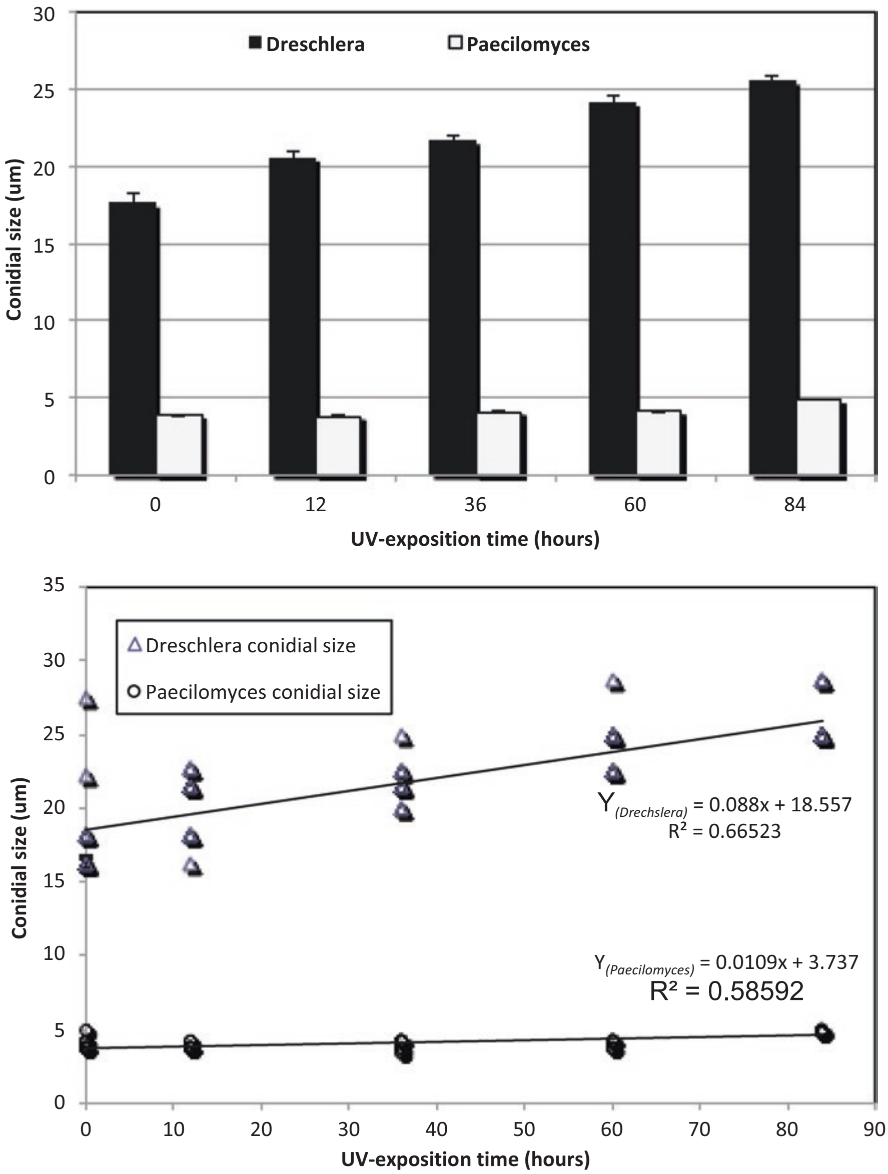

Fig. 3 The conidial size (m) of Paecilomyces spp. and *Dreschlera* spp. increases in response to increased ultraviolet radiations (UV-B, UV-A). (Abu-Elsaoud and Abdel-Azeem unpublished data)

which are species-specific. The ultraviolet (UV) spectrum of the sun's radiation is the most harmful and mutagenic. Most fungal conidia are susceptible to mortality when exposed to direct sunlight for a few hours. Conidia are killed by UV-A and UV-B rays from the sun. Sublethal UV light exposure can decrease the speed and

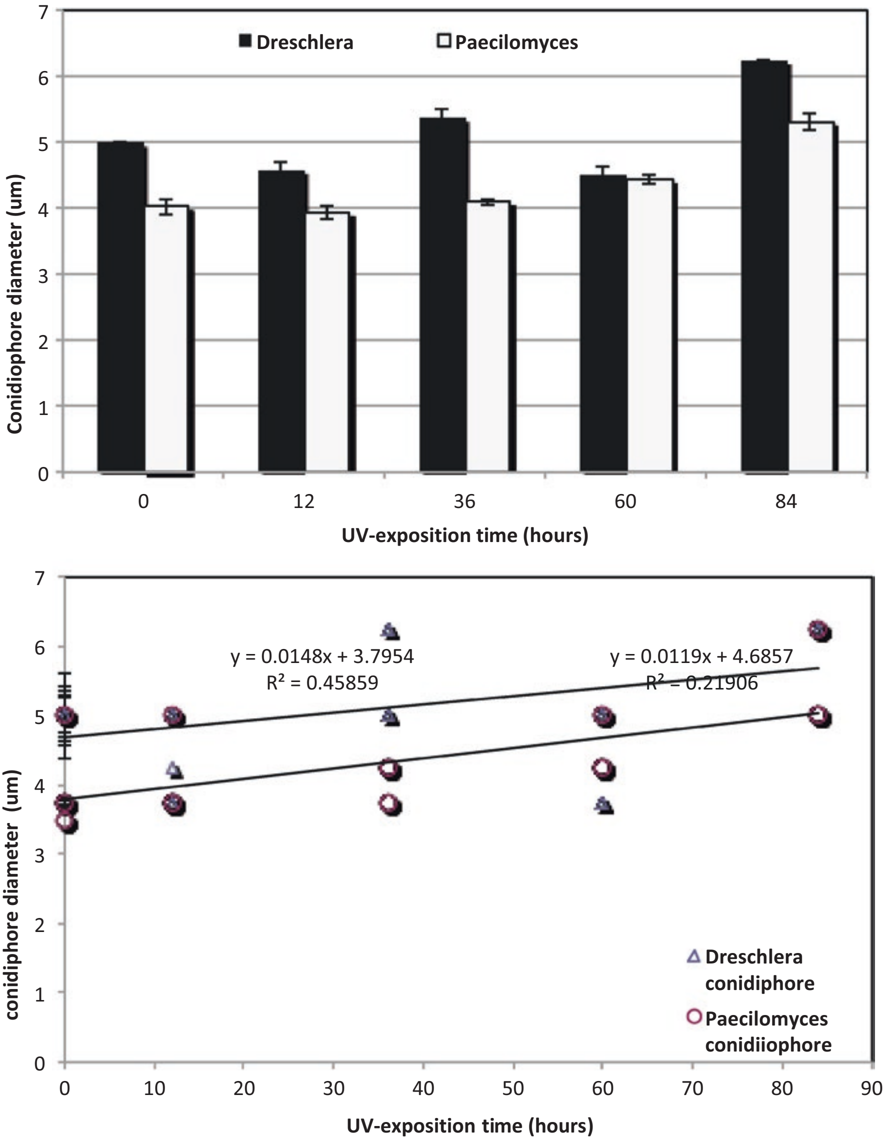

Fig. 4 The conidiophore diameter (m) of *Paecilomyces* sp. and *Dreschlera* sp. increases when exposed to higher amounts of ultraviolet radiations (UV-B, UV-A). (Abu-Elsaoud and Abdel-Azeem unpublished data)

pathogenicity of conidial germination as well as kill conidia, reducing the number and spread of the fungal population. This page attempts to provide readers with an overview of the key systems involved in UV radiation defence and healing, with a particular emphasis on how these mechanisms influence conidia. The methods used

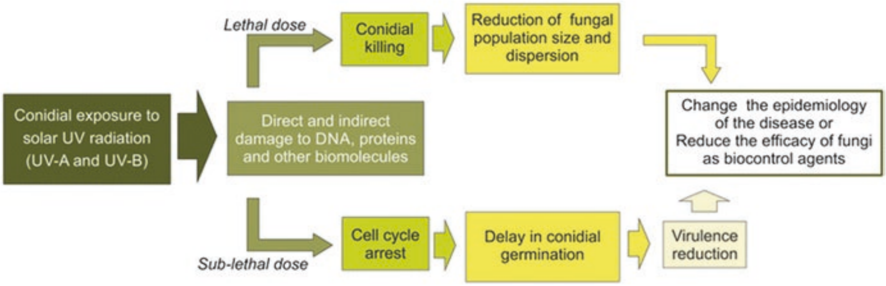

Fig. 5 The biological and molecular impacts of solar UV radiation on conidia and their ability to operate. (Source: Braga et al. 2015)

to create sun radiation-resistant strains of fungal species of interest, such as entomopathogens, will also be discussed. To further understand how solar UV radiation affects conidia on a molecular and physiological level, as well as how conidia respond functionally, refer to Fig. 5 (Braga et al. 2015).

3 Climate Warming

3.1 Plant Responses to Climate Warming

Tree growth and other physiological processes are very sensitive to temperature. A rise of 2–5 °C is forecast for this century, creating circumstances for numerous species that have never been seen before in evolutionary history. Sedentary and living for far longer periods of time than animals, plants, and especially trees, may require physiological adaptations to greater temperatures. But most plants can adjust to new conditions, and they typically do so in ways that maintain or even improve their carbon gain. Climate change has led to adaptations that increase carbon intake and growth, such as reduced respiration rates (Atkin and Tjoelker 2003), increased leaf areas (Way and Oren 2010), and even increased assimilation rates at warmer growth temperatures (Way and Sage 2008). In addition, most species may raise their thermal optimum of photosynthesis in response to rising temperatures (Crous et al. 2013; Way and Oren 2010) (Fig. 6). "Thermal acclimation" refers to the process by which a plant's physiology adapts to different temperatures used for growth. In most cases, the thermal ideal of photosynthesis will alter by a fraction of a degree for every degree that the growth temperature changes. By allowing plants to function at extremely high temperatures without a decrease in photosynthetic rates, raising the temperature ideal of photosynthesis has the potential to greatly mitigate the negative effects of warming (Fig. 6). Furthermore, in comparison to non-adaptive respiration rates, lower respiration rates with warming minimise carbon loss (Atkin et al. 2015). Large-scale changes in plant fluxes of respiration and photosynthesis will impact

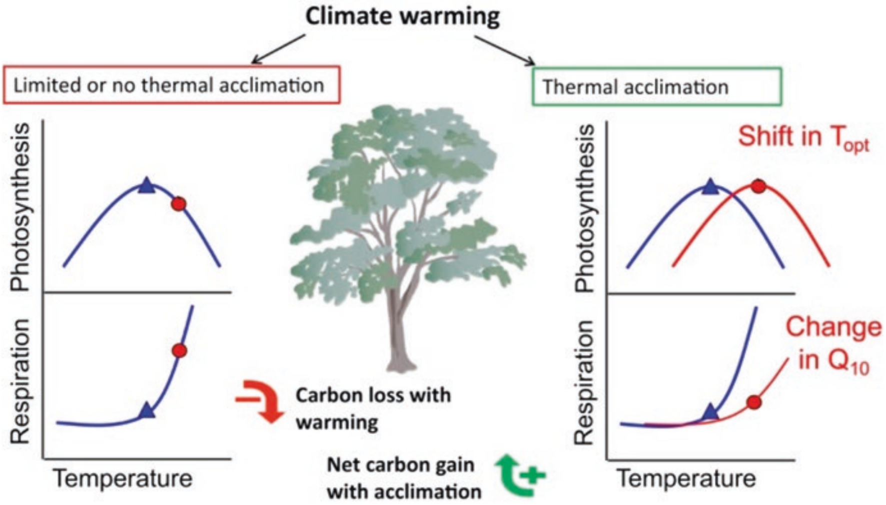

Fig. 6 Reduced complexity version of the physiological responses plants can make to rising temperatures throughout time (i.e., thermal acclimation). Temperature increases (red dots) and higher respiration (blue dots) relative to ambient conditions (left picture) both lead to lower rates of carbon uptake through photosynthesis. In reaction to rising temperatures, plants often move to a higher temperature optimum for photosynthesis (Shift in Topt), which allows them to keep their photosynthetic rates constant even as the temperature rises (compare red with blue lines in upper right panel). Consider the case when respiration is equal at the new growth temperature compared to ambient conditions, but with a lower slope, to see how thermal adaptation in respiration (Change in Q 10) can reduce carbon loss due to warming temperatures (compare red with blue lines in bottom right panel). (Source: Crous 2019)

the future degree of climate warming because plants affect global and regional temperature (Dusenge et al. 2019).

The climatic conditions to which a species is used have a role in determining how well it adapts to its new environment. When temperatures rise, many plant and animal species respond positively by increasing their rate of development and photosynthetic ability (Gunderson et al. 2009; Way and Sage 2008). On the other hand, research conducted in warmer climes showed that tree growth and carbon acquisition are lower in species native to warmer low-latitude conditions, as is the species' photosynthetic capability (Crous et al. 2013; Feeley et al. 2007). This data suggests that warmer-grown animals have a restricted physiological potential to adapt to higher temperatures. Species native to the equator, which experience relatively constant temperatures throughout the year, may be less able to adapt to rising global temperatures than those native to colder regions (higher latitudes), where seasonal temperature swings are more pronounced. Species that live at lower latitudes are also more likely to be operating at their thermal optimum (Crous et al. 2018; Doughty and Goulden 2008). As a result, the tropical rainforests, the most productive ecosystem on Earth, may lose some of their capacity to act as a carbon sink if the global average temperature continues to rise.

Plant responses to warming can be modulated by a number of other variables, including, but not limited to, increased (CO_2), nutrient availability, and changing precipitation patterns. Drought stress is anticipated to rise as a result of changes in rainfall patterns, the frequency of heatwaves, and the intensity of those heatwaves, all of which reinforce the negative impacts of higher temperatures. Warmer temperatures not only slow development, but also hinder seed generation and dissemination, which can ultimately lead to fewer seedling establishments and widespread forest dieback (Allen et al. 2010). Climate change has several consequences, including altered plant communities and decreased or modified distribution ranges of several plant species (Harsch and HilleRisLambers 2016).

3.2 Climate Affects Symbiotic Fungal Endophyte Diversity and Performance

The genetic diversity of endophytic fungi, which are microorganisms found on the surfaces of plants, is exceptionally great (Rodriguez et al. 2009). As a result, they can alter a plant's growth, offspring, and resistance to predators and adverse conditions (Cosme et al. 2016; Kivlin et al. 2013; Mayerhofer et al. 2013; Oberhofer et al. 2014; Rho et al. 2018; Rodriguez et al. 2008). Increased nitrogen absorption by host plants is one positive effect of endophytes (Afkhami and Strauss 2016; Aguilar-Trigueros and Rillig 2016; Behie and Bidochka 2014; Clay and Holah 1999; Rudgers et al. 2004, 2005) have all shown that endophytes have an impact on the overall structure and function of plant communities and the ecological webs that connect them (e.g. herbivores and their parasitoids; Omacini et al. 2001). The genus Neotyphodium and its asexual stage, Epichlo, have been used in a small number of experiments to teach us about fungal endophytes. It is not feasible to undertake randomised controlled trials to validate the ecological activities of most fungal endophytes due to their infamous difficulty to cultivate.

One of the most notable features of this important group of fungal endophytes is the wide host and geographic ranges of the species that make up the Serendipitaceae family, which is part of the order Sebacinales (Garnica et al. 2016; Weiß et al. 2011). Previous studies have demonstrated that Serendipita indica (Piriformospora indica) improves plant growth and modulates plant nutrition and tolerances to biotic and abiotic stresses, however these studies have mostly focused on S. indica (Achatz et al. 2010; Barazani et al. 2005; Gill et al. 2016; Waller et al. 2005). Tübingen coworkers and I have recently identified and cultured Serendipita herbamans, another member of the Serendipitaceae family that is widespread and associated with a wide range of host species and environmental conditions across Central Europe (Riess et al. 2014).

Soil microorganisms may have an impact on both plant growth and stress resistance, albeit how exactly they do so may differ from host to host. As a result, plant-microbe interactions aid in the development of plant communities, and there is growing evidence that they play a role in the spread of invasive plant species (Callaway et al. 2004; Dawson and Schrama 2016; Inderjit and van der Putten 2010; Klironomos 2002). Plants may profit from or be harmed by the microorganisms that live on them (Bever et al. 2012; van der Putten et al. 2013). If exotics accumulate biota that has a net favourable effect on the plant, they may have an advantage over locals. This could happen if the imported region does not have the same natural illnesses as the exotic does (Callaway et al. 2011; Maron et al. 2014; Mitchell and Power 2003; Reinhart et al. 2003). It has been suggested that the introduction of exotic plants into an area can have a negative effect on the soil biota by either increasing the number of diseases that attack native plants (Mangla and Callaway 2008) or by disrupting the interactions between mutualists and native plants (Meinhardt and Gehring 2012; Stinson et al. 2006).

Many studies on plant-microbe interactions and plant invasion have focused on soil-borne microbes rather than endophytes, despite the fact that fungal endophytes are apparently widespread and diverse also in invasive plant populations (Clay et al. 2016; Shipunov et al. 2008). A remarkable set of research by Aschehoug et al. (2012, 2014) showed how the leaf endophyte Alternaria alternata causes the invasive knapweed (Centaurea stoebe) highly effective and allelopathic towards native North American grasses.

3.3 Climate Change and Fungal Pathogens

Growing evidence suggests environmental factors have a significant influence in the emergence and resurgence of infectious illnesses, notably those caused by fungus and other fungal infections (El-Sayed and Kamel 2020; Wu et al. 2016; Nnadi and Carter 2021). The United Nations Framework Convention on Climate Change defines climate change as “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods,” suggesting that climate change may lead to the emergence of new fungal diseases (Farber 2021). Reference: (Garcia-Solache and Casadevall 2010). The possible role of viruses and bacteria in epidemics and pandemics is well discussed, but fungus should not be overlooked. Fungi may grow saprotrophically, producing huge amounts of infectious spores, and infecting new hosts does not necessitate direct contact between them. Despite these challenges, no vaccines have been developed specifically for fungal infections (Casadevall 2019). To be sure, fungi appear to be the only organisms capable of triggering total host extinction (Fisher et al. 2012).

Most fungal species cannot infect animals and establish lifelong infections because they cannot tolerate high temperatures. While a rise in disease-causing organisms is possible as a result of climate change’s sluggish adaptation to warming temperatures, fungi can be taught to gain thermotolerance (Casadevall 2020; de Crecy et al. 2009). Climate change also increases the likelihood that pathogenic

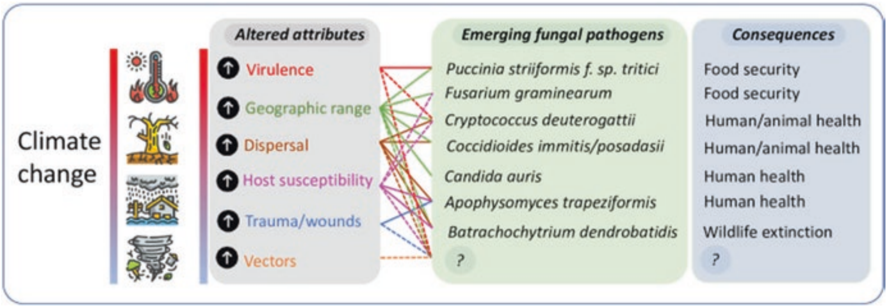

Fig. 7 Climate change's impact on the development of fungal diseases. Climate change modifies the characteristics of the fungus, its habitat, and its host, which can lead to the creation of novel, unusual, or adaptable fungal species, with repercussions for human health, biodiversity, and food security. On this diagram, solid lines between characteristics and fungal species represent associations supported by published research, whereas dashed lines represent associations that are likely but unconfirmed. "?" signifies the advent of as-yet-unidentified fungus species with unclear repercussions. (Source: Nnadi and Carter 2021)

organisms or the vectors that carry them may move to new locations, perhaps resulting in the emergence of diseases that have not been seen in those areas before (Casadevall 2020). Mold may be spread and aerosolized during climate-related environmental disruptions like floods, storms, and hurricanes, or it can be implanted via traumatic wounds and cause diseases from previously identified fungal species. Figure 7 depicts the potential consequences of climate change through the lens of emergent fungus and its effects, as well as the possibility that new and undiscovered species will emerge.

3.4 Climate Affects Symbiotic Fungal Endophyte Diversity and Performance

Because water is such a crucial factor in a plant's survival and growth, its drought tolerance can have far-reaching effects on production, variety, and dispersion (Knapp and Smith 2001; Lauenroth and Sala 1992). That this is the case has been demonstrated (Archaux and Wolters 2006; Craine et al. 2013; Knapp et al. 2002; Tilman and El Haddi 1992). Many climate models forecast broad increases in drought frequency and intensity in the future, therefore plants' capacity to tolerate drought will likely grow more essential (Meehl et al. 2007; Schoof et al. 2010; Seager et al. 2007; Solomon et al. 2007). Understanding the processes underpinning drought resistance is crucial for optimising plant growth in water-limited conditions. There is mounting evidence that microbial symbionts can play a role in mediating plant responses to drought and other stresses (e.g., Augé 2001; Márquez et al. 2007; Xu et al. 2008), despite the fact that most studies of plant drought resistance have focused on the plant's physiology and genetics in its abiotic environment.

Common plant symbionts, fungal endophytes, can have a significant impact on how well plants tolerate drought. Osmotic adjustment and other drought tolerance mechanisms may be affected by these factors (Malinowski and Belesky 2000; Morsy et al. 2010; Rodriguez et al. 2009, 2010; Waller et al. 2005). Host plants that were colonised by endophytes during drought showed increased biomass production, decreased evaporation, and increased resistance to water stress (Elmi and West 1995; Kane 2011; Kannadan and Rudgers 2008; Rodriguez et al. 2008). However, not all endophytes are beneficial to their host plants. Actually, the presence of certain endophytes can cause a decline in biomass and an increase in transpiration rates in host plants (Arnold and Engelbrecht 2007; Cheplick 2004; Kleczewski et al. 2012). Complex variables may explain why endophyte function varies between fungal species, genotypes, and habitats (Cheplick 2004; Morse et al. 2007; Rodriguez and Redman 2008).

How and what fungal endophytes perform in communities are likely influenced by a variety of factors, including location, ecology, and evolution (Leibold et al. 2004). Although most assume that bacteria may spread globally, there is mounting evidence that their transmission is confined to regional scales at most (Kivlin et al. 2011; Martiny et al. 2011; Peay et al. 2010; Waldrop and Firestone 2006). Spatial structure and species turnover may result from limited dispersion. For instance, Márquez et al. (2008) discovered that as they travelled further from the coast of Spain, the endophyte community in two different grasses became less similar. Species will naturally separate into several populations in places with varying habitats if there is sufficient dispersal (Leibold et al. 2004). By analysing community data from 158 research, Cottenie (2005) showed that 44% of communities were structured by species sorting, 29% by a combination of species sorting and dispersion effects, and 8% by spatial factors that likely indicate neutral processes or patch dynamics. The review did not consider symbiotic or terrestrial microbial populations. The nonclavicipitaceous endophytes of above-ground plant tissues discussed here are often a result of horizontal transmission from their natural habitats (e.g., soil, other plants, Rodriguez et al. 2009). Horizontal spread of endophytes is less likely to result in symbiotic relationships than vertical transmission via seeds (Higgins et al. 2011; Rodriguez et al. 2009). What's more plausible is that endophytes are influenced by a combination of environmental variables and the way space evolves through time. For instance, Arnold and Lutzoni (2007) discovered that, for 28 host species spanning the northern tundra to the tropical jungle, latitude was the strongest predictor of endophyte diversity. Likely causes include restricted range and a lack of suitable habitat.

The key to developing a prediction paradigm for endophyte function in symbiosis is understanding how endophyte dispersion corresponds to their functional capacities. Since endophyte function is linked to some particularly hostile environments, environmental filtration and local adaptation may both play a role in shaping species' ranges in such settings. Several plant species, for instance, gained salt and heat tolerance through endophytes that had been separated from salty and geothermal habitats (Redman et al. 2002; Rodriguez et al. 2008). Both past drought patterns and current drought levels are likely to operate as environmental filters when we think about drought stress (Evans and Wallenstein 2012). Current endophyte communities may have emerged in reaction to previous moisture circumstances, but it is unknown how long-term drought stress influences the available species pool. If dispersal is the major controller of endophyte distributions, however, these organisms will be dispersed in a fashion that is unrelated to their function, as established by the spatial arrangement of sites. It may be possible to better anticipate the involvement of endophytes in plants under different environmental conditions if we understand the relative impact of environmental variables (species sorting) and spatial processes (neutral or mass effects) in endophyte community distributions. By learning more about endophytes' function in drought resistance, we could be better able to foresee how plants will react to drought in the future.

3.5 Effect of Climate Change on Fodder and Forage Availability and Livestock

The farming industry as a whole is heavily invested in animal domestication. It is not uncommon for there to be lone or several small farmers in each country of the region, each with between one and five ruminants. To put it another way, climate change has an immediate effect on the production of feed and livestock. The effects of climate change in the 1990s were disastrous across the world. Global surface temperatures increased by 0.6 °C over the twentieth century, and more rises are expected during the twentieth century. At now, the ability of ruminants to transform low-quality forages into nutritious human food is threatened by the global warming phenomenon. The cattle business is a major source of greenhouse gas emissions, including methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). The International Panel on Climate Change (IPCC) estimates that ruminants in India, Pakistan, and Bangladesh release as much carbon dioxide as 950 metric tonnes worth of methane every year. More study is required because of the large gap between IPCC estimates and actual situations. There are more than 125 million buffalo in the surrounding area. It's possible that ruminants fed a diet high in roughage, although economically feasible, will emit more of the greenhouse gas methane than ruminants on diets more typical of the rest of the globe (Godde et al. 2021).

The amount of food production and the health of the global environment are both linked to the intensity with which agriculture is practised. Half of all farmable land is already in use, either for extensive livestock ranching or large-scale crop production. The sustainability of food production, aquatic ecosystems, and societal services will be severely tested by the predicted doubling of global food demand over the next 50 years. Most of the world's population lives on grasslands, which account for 40% of the planet's surface and are particularly vulnerable because of this. The ability of the world's grasslands to sustain human, plant, and animal life has diminished as a result of overgrazing. Grasslands are changing due to human activities such as agriculture, urbanisation, and industry. The warming effect of atmospheric gas buildup over the coming century makes it evident that the world's resource allocation and consumption must alter. Most scientists agree that climate change is happening due to human actions like burning fossil fuels, clearing forests, and using chemical fertilisers, and that poorer nations will be hit harder by the effects of this shift.

Greenhouse gases, like CO_2, methane, and nitrous oxide, that humans release into the atmosphere are a major cause of global warming. The higher prevalence of floods, droughts, cyclones, and heavy rains in recent times is evidence that the accumulation of gases is affecting the climate change globally. Ruminant animals are the most effective users of natural grassland and serve a variety of purposes in global agricultural systems. They provide as a source of food and revenue for both rural and urban dwellers, facilitate movement by providing transport and traction, and generate value-added commodities that can have a multiplicative influence on the economy and the demand for a wide range of services. Reports on the effects of global warming on agriculture indicate that the nations of the tropics and subtropics will be particularly hard hit. The development and maturity of plants, as well as the quality of their forage, can be affected by variations in environmental conditions from year to year, season to season, and location. Because of this, estimating the nutrient content of forages and the variety in how they will be used by ruminants is more difficult than it needs to be. Changes in chemical composition and senescence caused by environmental factors such temperature, moisture, sunlight, soil composition, and pathogens can reduce fodder quality and therefore, intake and digestion. Production and feeding of quality forages, which are impacted by climate and soil, are the main constraints on sustainable livestock production in the South Asian area. Despite the importance of studying the impact of environmental changes on fodder productivity and quality in the Asian area, relatively few research has been done on the topic. The elements that affect plant growth and quality are discussed in this work.

Reasons for the climate change are related to the environment. Cause of global warming. Methane (CH_4), carbon dioxide (CO_2), halocarbons, ozone, nitrous oxide (N_2O), water vapour and aerosols are the most significant greenhouse gases. Human activity is the primary contributor to the steady increase of carbon dioxide in the atmosphere (Fig. 8).

Carbon dioxide levels are rising at a rate of roughly 0.3% each year, according to measurements taken throughout the world. They are expected to reach 600 parts per million by the end of the twenty-first century, from their current level of 370 parts per million (Houghton et al. 1990). Humans contribute at a rate of 1.9% year (Marland 1990; Watson et al. 1992), with most of the increase coming from wealthy countries. The United States and the United Kingdom are responsible for an estimated 18.9 and 8.9 tones, respectively, while India contributes a far more modest 1 tone. Carbon dioxide emissions at a worldwide level increased by 1.6 gigatons per year due to deforestation (Watson et al. 1990, 1992). In 1990, it was projected that Bangladesh produced 13.5–15.5 and 61.2 thousand Gg of carbon dioxide annually from the burning of fossil fuels and biomass, respectively (Ahmed et al. 1996; DOE 1997).

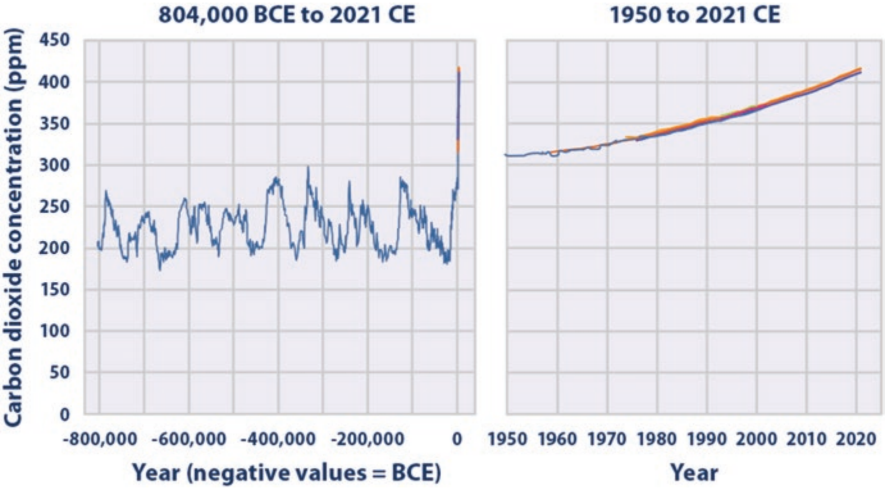

Fig. 8 Global atmospheric concentrations of carbon dioxide over time. (Source: US EPA 2022)

The death of all above-ground vegetation and the resulting shortage of forage can have a devastating effect on animal output. Due to slower stem development and a resultant leafier sward, digestibility is unaffected by or even improved by moderate moisture stress (Wilson 1983). This is crucial information for plants that need a constantly moist environment to thrive. Forage growth and productivity are more severely impacted by water stress than forage quality. Increases in nitrogen (N) content (Wilson and Ng 1975), minerals (Abdel Rahman et al. 1971), and soluble carbohydrates (SC) in forage have all been linked to water stress(Ford and Wilson 1981). Alfalfa output drops by 49% when water stress delays plant development, leading to a higher leaf-to-stem ratio (18%) and higher digestibility (8%). It also caused a 10% boost in CP in the stem and a 14% drop in the leaves (Halim et al. 1989). Forage grasses and legumes exhibited analogous tendencies. Where soil phosphorus levels are low, animal output may be constrained because phosphorus concentrations are often low in water-stressed feed (Abdel Rahman et al. 1971). Elevated levels of alkalinity, hydrocyanic acid, or tannins in forages might diminish their appeal (Hoveland and Monson 1980). Grass that has been sitting in the rain for too long or that grows in low-lying regions may have a high call wall content but low CP (Pate and Snyder 1979). Lower cell wall digestibility from increased lignifications is a common result of high growing temperatures, which has important implications for food quality (Ford et al. 1979). High temperatures have a more noticeable impact on grass quality than legume quality. Plants cultivated at low temperatures are more digestible than those produced at high temperatures, despite the fact that both had the same age at harvest (Fig. 3). A decrease in the N content and digestibility of grasses and tropical legumes may accompany the effect of drought on production and composition of forage legumes and grasses in tropical climates (Wilson and Mannetje 1978).

3.5.1 Nutritional Factors

Fodder, horticultural, vegetable, forest, livestock, and fishery production are all impacted by climate change, as is the capacity to supply the world's ever-increasing food demand. Rapid climate change hinders ecosystems' and species' ability to adapt, speeding up biodiversity loss. Human security is threatened by climate change and the corresponding loss of biodiversity because of the potential for drastic shifts in the food chain on which we rely, the potential for water sources to change, recede, or disappear, and the potential for medicines and other resources to be affected. It may become more challenging for humans to get some resources if plant and flora populations decline or disappear. Climate change in the region has had a significant impact on a wide range of physical and biological systems, and there are signs to suggest it has also had an impact on social and economic structures. As a result of the summer monsoon circulation, India's climate and weather are dominated by the world's most significant seasonal mode of precipitation. Precipitation variability beyond this seasonal mode is primarily inter-annual and intra-seasonal, resulting in extremes in seasonal anomalies that cause widespread droughts and floods and short-period precipitation extremes that take the form of torrential downpours or protracted breaks on the synoptic scale. In addition, India's climate has cold waves throughout the north during the winter and hot waves in the bulk of the nation during the pre-monsoon season. As a significant natural catastrophe connected to climatic extremes, tropical cyclones are responsible for severe destruction and loss of life when they strike coastal areas with heavy rain, strong winds, and storm surges. Human activities are affected by these extremes, thus more attention is needed from all levels of society to combat this threat.

3.5.2 Effect of Climate on Fodder

As a crop or plant, fodder has a high level of variety and the ability to withstand moderate effects of climate change. However, in any particular area, the predominating source of feed is the vegetation and animals that evolved there organically. However, there is a wide range in the development and production capacity of excellent green fodder due to the fact that different cultivable cereals fodder, roughes, legumes, trees, and perennial grasses have distinct climatic requirements. Green forage varied in composition and quality as the climate did. In addition, the same affected the health of animals and the quality of animal products.

3.5.3 Effect of Climate on Livestock

Loss of grazing land, a shortage of forage because of slowing growth and lower green fodder yield (GFY), and lower milk, egg, and meat production are the most notable consequences of climate change for the livestock industry. There will be a drop in income and an increase in rural residents' need for food stamps and unemployment as a result of all these factors. Weather and extreme events have direct effects on animal health, growth, and reproduction; (a) the availability and cost of livestock feed grains; (b) the production and quality of pastures and forage crops used in livestock production; (c) the distribution of livestock diseases and pests; and (d) the direct effects of weather on livestock. However, it is unclear how global climate change may affect animal productivity because most research has been conducted in industrialised nations and very little in Africa, Asia, and South America. Threats to the animal husbandry industry include habitat loss, altered environmental conditions, disease outbreaks, reproductive obstacles, and decreased productivity.

References

Abdel Rahman AA, Shalaby AF, El Monayeri MO (1971) Effect of moisture stress on metabolic products and ions accumulation. Plant Soil 34:65–90. https://doi.org/10.1007/BF01372762

Abu-Elsaoud AM, Abdel-Azeem AM (2020) Light, electromagnetic spectrum, and photostimulation of microorganisms with special reference to chaetomium. In: Abdel-Azeem AM (ed) Recent developments on genus chaetomium, fungal biology. Springer, Cham, pp 377–393. https://doi.org/10.1007/978-3-030-31612-9_14

Achatz B, von Rüden S, Andrade D, Neumann E, Pons-Kühnemann J, Kogel K-H, Franken P, Waller F (2010) Root colonization by Piriformospora indica enhances grain yield in barley under diverse nutrient regimes by accelerating plant development. Plant Soil 333:59–70. https://doi.org/10.1007/s11104-010-0319-0

Afkhami ME, Strauss SY (2016) Native fungal endophytes suppress an exotic dominant and increase plant diversity over small and large spatial scales. Ecology 97:1159–1169. https://doi.org/10.1890/15-1166.1

Aguilar-Trigueros CA, Rillig MC (2016) Effect of different root endophytic fungi on plant community structure in experimental microcosms. Ecol Evol 6:8149–8158. https://doi.org/10.1002/ece3.2416

Ahmed AU, Islam K, Reazuddin M (1996) An inventory of greenhouse gas emissions in Bangladesh: initial results. R Swed Acad Sci Ambio 25:300–303

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EH, Gonzalez P, Fensham R, Zhang Z, Castro J, Demidova N, Lim J-H, Allard G, Running SW, Semerci A, Cobb N (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manag Adapt For For Manag Chang Clim 259:660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Archaux F, Wolters V (2006) Impact of summer drought on forest biodiversity: what do we know? Ann For Sci 63:645–652. https://doi.org/10.1051/forest:2006041

Arnold AE, Engelbrecht BMJ (2007) Fungal endophytes nearly double minimum leaf conductance in seedlings of a neotropical tree species. J Trop Ecol 23:369–372

Arnold AE, Lutzoni F (2007) Diversity and host range of foliar fungal endophytes: are tropical leaves biodiversity hotspots? Ecology 88:541–549. https://doi.org/10.1890/05-1459

Aschehoug ET, Metlen KL, Callaway RM, Newcombe G (2012) Fungal endophytes directly increase the competitive effects of an invasive forb. Ecology 93:3–8. https://doi.org/10.1890/11-1347.1

Aschehoug ET, Callaway RM, Newcombe G, Tharayil N, Chen S (2014) Fungal endophyte increases the allelopathic effects of an invasive forb. Oecologia 175:285–291. https://doi.org/10.1007/s00442-014-2891-0

Atkin OK, Tjoelker MG (2003) Thermal acclimation and the dynamic response of plant respiration to temperature. Trends in Plant Science 8:343–351. https://doi.org/10.1016/S1360-1385(03)00136-5

Atkin OK, Bloomfield KJ, Reich PB, Tjoelker MG, Asner GP, Bonal D, Bönisch G, Bradford MG, Cernusak LA, Cosio EG, Creek D, Crous KY, Domingues TF, Dukes JS, Egerton JJG, Evans JR, Farquhar GD, Fyllas NM, Gauthier PPG, Gloor E, Gimeno TE, Griffin KL, Guerrieri R, Heskel MA, Huntingford C, Ishida FY, Kattge J, Lambers H, Liddell MJ, Lloyd J, Lusk CH, Martin RE, Maksimov AP, Maximov TC, Malhi Y, Medlyn BE, Meir P, Mercado LM, Mirotchnick N, Ng D, Niinemets Ü, O'Sullivan OS, Phillips OL, Poorter L, Poot P, Prentice IC, Salinas N, Rowland LM, Ryan MG, Sitch S, Slot M, Smith NG, Turnbull MH, VanderWel MC, Valladares F, Veneklaas EJ, Weerasinghe LK, Wirth C, Wright IJ, Wythers KR, Xiang J, Xiang S, Zaragoza-Castells J (2015) Global variability in leaf respiration in relation to climate, plant functional types and leaf traits. New Phytol 206:614–636. https://doi.org/10.1111/nph.13253

Augé RM (2001) Water relations, drought and vesicular-arbuscular mycorrhizal symbiosis. Mycorrhiza 11:3–42. https://doi.org/10.1007/s005720100097

Bais AF, McKenzie RL, Bernhard G, Aucamp PJ, Ilyas M, Madronich S, Tourpali K (2015) Ozone depletion and climate change: impacts on UV radiation. Photochem Photobiol Sci 14:19–52. https://doi.org/10.1039/C4PP90032D

Barazani O, Benderoth M, Groten K, Kuhlemeier C, Baldwin IT (2005) Piriformospora indica and Sebacina vermifera increase growth performance at the expense of herbivore resistance in Nicotiana attenuata. Oecologia 146:234–243. https://doi.org/10.1007/s00442-005-0193-2

Beardall J, Sobrino C, Stojkovic S (2009) Interactions between the impacts of ultraviolet radiation, elevated CO2, and nutrient limitation on marine primary producers. Photochem Photobiol Sci 8:1257–1265. https://doi.org/10.1039/b9pp00034h

Beaugrand G, Reid PC, Ibañez F, Lindley JA, Edwards M (2002) Reorganization of North Atlantic marine copepod biodiversity and climate. Science 296:1692–1694. https://doi.org/10.1126/science.1071329

Beaugrand G, Brander KM, Alistair Lindley J, Souissi S, Reid PC (2003) Plankton effect on cod recruitment in the North Sea. Nature 426:661–664. https://doi.org/10.1038/nature02164

Behie SW, Bidochka MJ (2014) Nutrient transfer in plant-fungal symbioses. Trends Plant Sci 19:734–740. https://doi.org/10.1016/j.tplants.2014.06.007

Bever JD, Platt TG, Morton ER (2012) Microbial population and community dynamics on plant roots and their feedbacks on plant communities. Annu Rev Microbiol 66:265–283. https://doi.org/10.1146/annurev-micro-092611-150107

Björn LO (ed) (2015) Photobiology. Springer, New York

Boelen P, Obernostere I, Vink AA, Buma AGJ (1999) Attenuation of biologically effective UV radiation in tropical Atlantic waters measured with a biochemical DNA dosimeter. Photochem Photobiol 69:34–40. https://doi.org/10.1111/j.1751-1097.1999.tb05303.x

Boyd PW, Strzepek R, Fu F, Hutchins DA (2010) Environmental control of open-ocean phytoplankton groups: now and in the future. Limnol Oceanogr 55:1353–1376. https://doi.org/10.4319/lo.2010.55.3.1353

Braga GUL, Rangel DEN, Fernandes ÉKK, Flint SD, Roberts DW (2015) Molecular and physiological effects of environmental UV radiation on fungal conidia. Curr Genet 61:405–425. https://doi.org/10.1007/s00294-015-0483-0

Britt AB (1996) DNA damage and repair in plants. Annu Rev Plant Physiol Plant Mol Biol 47:75–100. https://doi.org/10.1146/annurev.arplant.47.1.75

Buma A, Zemmelink H, Sjollema K, Gieskes W (1996) UVB radiation modifies protein and photosynthetic pigment content, volume and ultrastructure of marine diatoms. Mar Ecol Prog Ser 142:47–54. https://doi.org/10.3354/meps142047

Callaway RM, Thelen GC, Rodriguez A, Holben WE (2004) Soil biota and exotic plant invasion. Nature 427:731–733. https://doi.org/10.1038/nature02322

Callaway RM, Bedmar EJ, Reinhart KO, Silvan CG, Klironomos J (2011) Effects of soil biota from different ranges on Robinia invasion: acquiring mutualists and escaping pathogens. Ecology 92:1027–1035. https://doi.org/10.1890/10-0089.1

Casadevall A (2019) Global catastrophic threats from the fungal kingdom: fungal catastrophic threats. Curr Top Microbiol Immunol 424:21–32. https://doi.org/10.1007/82_2019_161

Casadevall A (2020) Climate change brings the specter of new infectious diseases. J Clin Investig 130:553–555. https://doi.org/10.1172/JCI135003

Cheplick GP (2004) Recovery from drought stress in Lolium perenne (Poaceae): are fungal endophytes detrimental? Am J Bot 91:1960–1968. https://doi.org/10.3732/ajb.91.12.1960

Ciais P, Chris S, Govindasamy B, Bopp L, Brovkin V, Canadell J, Chhabra A, Defries R, Galloway J, Heimann M (2014) Carbon and other biogeochemical cycles. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel on Climate Change, pp 465–570

Clay K, Holah J (1999) Fungal endophyte symbiosis and plant diversity in successional fields. Science 285:1742–1745. https://doi.org/10.1126/science.285.5434.1742

Clay K, Shearin ZRC, Bourke KA, Bickford WA, Kowalski KP (2016) Diversity of fungal endophytes in non-native Phragmites australis in the Great Lakes. Biol Invasions 18:2703–2716. https://doi.org/10.1007/s10530-016-1137-y

Cloern JE, Schraga TS, Lopez CB, Knowles N, Grover Labiosa R, Dugdale R (2005) Climate anomalies generate an exceptional dinoflagellate bloom in San Francisco Bay. Geophys Res Lett 32:n/a-n/a. https://doi.org/10.1029/2005GL023321

Cosme M, Lu J, Erb M, Stout MJ, Franken P, Wurst S (2016) A fungal endophyte helps plants to tolerate root herbivory through changes in gibberellin and jasmonate signaling. New Phytol 211:1065–1076. https://doi.org/10.1111/nph.13957

Cottenie K (2005) Integrating environmental and spatial processes in ecological community dynamics. Ecol Lett 8:1175–1182. https://doi.org/10.1111/j.1461-0248.2005.00820.x

Craine JM, Ocheltree TW, Nippert JB, Towne EG, Skibbe AM, Kembel SW, Fargione JE (2013) Global diversity of drought tolerance and grassland climate-change resilience. Nat Clim Chang 3:63–67. https://doi.org/10.1038/nclimate1634

Crous KY (2019) Plant responses to climate warming: physiological adjustments and implications for plant functioning in a future, warmer world. Am J Bot 106:1049–1051. https://doi.org/10.1002/ajb2.1329

Crous KY, Quentin AG, Lin Y-S, Medlyn BE, Williams DG, Barton CVM, Ellsworth DS (2013) Photosynthesis of temperate Eucalyptus globulus trees outside their native range has limited adjustment to elevated CO2 and climate warming. Glob Chang Biol 19:3790–3807. https://doi.org/10.1111/gcb.12314

Crous KY, Drake JE, Aspinwall MJ, Sharwood RE, Tjoelker MG, Ghannoum O (2018) Photosynthetic capacity and leaf nitrogen decline along a controlled climate gradient in provenances of two widely distributed Eucalyptus species. Glob Chang Biol 24:4626–4644. https://doi.org/10.1111/gcb.14330

Damian DL, Matthews YJ, Phan TA, Halliday GM (2011) An action spectrum for ultraviolet radiation-induced immunosuppression in humans. Br J Dermatol 164:657–659. https://doi.org/10.1111/j.1365-2133.2010.10161.x

Dawson W, Schrama M (2016) Identifying the role of soil microbes in plant invasions. J Ecol 104:1211–1218. https://doi.org/10.1111/1365-2745.12619

de Crecy E, Jaronski S, Lyons B, Lyons TJ, Keyhani NO (2009) Directed evolution of a filamentous fungus for thermotolerance. BMC Biotechnol 9:74. https://doi.org/10.1186/1472-6750-9-74

DOE (1997) Global climate change – Bangladesh episode. Department of Environment

Doughty CE, Goulden ML (2008) Are tropical forests near a high temperature threshold? J Geophys Res 113:n/a–n/a. https://doi.org/10.1029/2007JG000632

Dusenge ME, Duarte AG, Way DA (2019) Plant carbon metabolism and climate change: elevated CO_2 and temperature impacts on photosynthesis, photorespiration and respiration. New Phytol 221:32–49. https://doi.org/10.1111/nph.15283

Elmi AA, West CP (1995) Endophyte infection effects on stomatal conductance, osmotic adjustment and drought recovery of tall fescue. New Phytol 131:61–67. https://doi.org/10.1111/j.1469-8137.1995.tb03055.x

El-Sayed A, Kamel M (2020) Climatic changes and their role in emergence and re-emergence of diseases. Environ Sci Pollut Res Int 27:22336–22352. https://doi.org/10.1007/s11356-020-08896-w

Evans SE, Wallenstein MD (2012) Soil microbial community response to drying and rewetting stress: does historical precipitation regime matter? Biogeochemistry 109:101–116

Farber DA (2021) The intersection of international disaster law and climate change law. YIDO 2:87–115. https://doi.org/10.1163/26662531_00201_005

Feeley KJ, Joseph Wright S, Nur Supardi MN, Kassim AR, Davies SJ (2007) Decelerating growth in tropical forest trees. Ecol Lett 10:461–469. https://doi.org/10.1111/j.1461-0248.2007.01033.x

Fisher MC, Henk DA, Briggs CJ, Brownstein JS, Madoff LC, McCraw SL, Gurr SJ (2012) Emerging fungal threats to animal, plant and ecosystem health. Nature 484:186–194. https://doi.org/10.1038/nature10947

Ford C, Wilson J (1981) Changes in levels of solutes during osmotic adjustment to water stress in leaves of four tropical pasture species. Funct Plant Biol 8:77. https://doi.org/10.1071/PP9810077

Ford C, Morrison I, Wilson J (1979) Temperature effects on lignin, hemicellulose and cellulose in tropical and temperate grasses. Aust J Agric Res 30:621. https://doi.org/10.1071/AR9790621

Fourtouni A, Manetas Y, Christias C (1998) Effects of UV-B radiation on growth, pigmentation, and spore production in the phytopathogenic fungus *Alternaria solani*. Can J Bot 76:2093–2099. https://doi.org/10.1139/b98-170

Fu F, Tatters A, Hutchins D (2012) Global change and the future of harmful algal blooms in the ocean. Mar Ecol Prog Ser 470:207–233. https://doi.org/10.3354/meps10047

Garcia-Solache MA, Casadevall A (2010) Global warming will bring new fungal diseases for mammals. mBio 1:e00061–e00010. https://doi.org/10.1128/mBio.00061-10

Garnica S, Riess K, Schön ME, Oberwinkler F, Setaro SD (2016) Divergence times and phylogenetic patterns of sebacinales, a highly diverse and widespread fungal lineage. PLoS One 11:e0149531. https://doi.org/10.1371/journal.pone.0149531

Gill SS, Gill R, Trivedi DK, Anjum NA, Sharma KK, Ansari MW, Ansari AA, Johri AK, Prasad R, Pereira E, Varma A, Tuteja N (2016) Piriformospora indica: potential and significance in plant stress tolerance. Front Microbiol 7:332

Godde CM, Mason-D'Croz D, Mayberry DE, Thornton PK, Herrero M (2021) Impacts of climate change on the livestock food supply chain; a review of the evidence. Glob Food Sec 28:100488. https://doi.org/10.1016/j.gfs.2020.100488

Görner H (1994) New trends in photobiology: photochemistry of DNA and related biomolecules: quantum yields and consequences of photoionization. J Photochem Photobiol B Biol 26:117–139. https://doi.org/10.1016/1011-1344(94)07068-7

Gunderson CA, O'Hara KH, Campion CM, Walker AV, Edwards NT (2009) Thermal plasticity of photosynthesis: the role of acclimation in forest responses to a warming climate: photosynthetic acclimation to warmer climates. Glob Chang Biol 16:2272–2286. https://doi.org/10.1111/j.1365-2486.2009.02090.x

Halim RA, Buxton DR, Hattendorf MJ, Carlson RE (1989) Water-stress effects on alfalfa forage quality after adjustment for maturity differences. Agron J 81:189–194. https://doi.org/10.2134/agronj1989.00021962008100020010x

Harsch MA, HilleRisLambers J (2016) Climate warming and seasonal precipitation change interact to limit species distribution shifts across Western North America. PLoS One 11:e0159184. https://doi.org/10.1371/journal.pone.0159184

He Y-Y, Häder D-P (2002) UV-B-induced formation of reactive oxygen species and oxidative damage of the cyanobacterium Anabaena sp.: protective effects of ascorbic acid and N-acetyl-l-cysteine. J Photochem Photobiol B Biol 66:115–124. https://doi.org/10.1016/S1011-1344(02)00231-2

Higgins KL, Coley PD, Kursar TA, Arnold AE (2011) Culturing and direct PCR suggest prevalent host generalism among diverse fungal endophytes of tropical forest grasses. Mycologia 103:247–260. https://doi.org/10.3852/09-158

Hogue VE, Wilkerson FP, Dugdale RC (2005) Ultraviolet-B radiation effects on natural phytoplankton assemblages of Central San Francisco Bay. Estuaries 28:190–203. https://doi.org/10.1007/BF02732854

Houghton JT, Jenkins GJ, Ephraums JJ (eds) (1990) Climate change: the IPCC scientific assessment. Cambridge University Press, Cambridge/New York

Hoveland CS, Monson WG (1980) Genetic and environmental effects on forage quality. In: Crop quality, storage, and utilization. Wiley, pp 139–168. https://doi.org/10.2135/1980.cropquality.c6

Huang S-J, Lin C-P, Mau J-L, Li Y-S, Tsai S-Y (2015) Effect of UV-B irradiation on physiologically active substance content and antioxidant properties of the medicinal caterpillar fungus Cordyceps militaris (Ascomycetes). Int J Med Mushrooms 17:241–253. https://doi.org/10.1615/intjmedmushrooms.v17.i3.40

Inderjit, van der Putten WH (2010) Impacts of soil microbial communities on exotic plant invasions. Trends Ecol Evol 25:512–519. https://doi.org/10.1016/j.tree.2010.06.006

Jones RL (ed) (2013) The molecular life of plants. Chichester/Hoboken, Wiley-Blackwell

Jones RL, Ougham H, Thomas H, Waaland S (eds) (2013) The molecular life of plants. Wiley-Blackwell, Chichester/Hoboken

Kane KH (2011) Effects of endophyte infection on drought stress tolerance of Lolium perenne accessions from the Mediterranean region. Environ Exp Bot 71:337–344. https://doi.org/10.1016/j.envexpbot.2011.01.002

Kannadan S, Rudgers JA (2008) Endophyte symbiosis benefits a rare grass under low water availability. Funct Ecol 22:706–713. https://doi.org/10.1111/j.1365-2435.2008.01395.x

Kivlin SN, Hawkes CV, Treseder KK (2011) Global diversity and distribution of arbuscular mycorrhizal fungi. Soil Biol Biochem 43:2294–2303. https://doi.org/10.1016/j.soilbio.2011.07.012

Kivlin SN, Emery SM, Rudgers JA (2013) Fungal symbionts alter plant responses to global change. Am J Bot 100:1445–1457. https://doi.org/10.3732/ajb.1200558

Kleczewski NM, Bauer JT, Bever JD, Clay K, Reynolds HL (2012) A survey of endophytic fungi of switchgrass (Panicum virgatum) in the Midwest, and their putative roles in plant growth. Fungal Ecol 5:521–529. https://doi.org/10.1016/j.funeco.2011.12.006

Klironomos JN (2002) Feedback with soil biota contributes to plant rarity and invasiveness in communities. Nature 417:67–70. https://doi.org/10.1038/417067a

Knapp AK, Smith MD (2001) Variation among biomes in temporal dynamics of aboveground primary production. Science 291:481–484. https://doi.org/10.1126/science.291.5503.481

Knapp AK, Fay PA, Blair JM, Collins SL, Smith MD, Carlisle JD, Harper CW, Danner BT, Lett MS, McCarron JK (2002) Rainfall variability, carbon cycling, and plant species diversity in a mesic grassland. Science 298:2202–2205. https://doi.org/10.1126/science.1076347

Lauenroth WK, Sala OE (1992) Long-term forage production of North American shortgrass Steppe. Ecol Appl 2:397–403. https://doi.org/10.2307/1941874

Leibold MA, Holyoak M, Mouquet N, Amarasekare P, Chase JM, Hoopes MF, Holt RD, Shurin JB, Law R, Tilman D, Loreau M, Gonzalez A (2004) The metacommunity concept: a framework for multi-scale community ecology: the metacommunity concept. Ecol Lett 7:601–613. https://doi.org/10.1111/j.1461-0248.2004.00608.x

Madronich S, McKenzie RL, Björn LO, Caldwell MM (1998) Changes in biologically active ultraviolet radiation reaching the Earth's surface. J Photochem Photobiol B Biol 46:5–19. https://doi.org/10.1016/S1011-1344(98)00182-1

Malinowski DP, Belesky DP (2000) Adaptations of endophyte-infected cool-season grasses to environmental stresses: mechanisms of drought and mineral stress tolerance. Crop Sci 40:923–940. https://doi.org/10.2135/cropsci2000.404923x

Mangla S, Callaway RM (2008) Exotic invasive plant accumulates native soil pathogens which inhibit native plants. J Ecol 96:58–67. https://doi.org/10.1111/j.1365-2745.2007.01312.x

Marcoval MA, Villafañe VE, Helbling EW (2007) Interactive effects of ultraviolet radiation and nutrient addition on growth and photosynthesis performance of four species of marine phytoplankton. J Photochem Photobiol B 89:78–87. https://doi.org/10.1016/j.jphotobiol.2007.09.004

Marland G (1990) Global and natural CO 2 emission from fossil fuel burning, cement production and gas, planning. In: Boden TA, Kancirk P, Farvell MP (eds) TRENDS' 1990: a compensation of date on global change. ORNL/CDIAC-36. Carbon Dioxide Information Analysis Centre, Oak Ridge National, Oak Ridge, pp 92–93

Maron JL, Klironomos J, Waller L, Callaway RM (2014) Invasive plants escape from suppressive soil biota at regional scales. J Ecol 102:19–27. https://doi.org/10.1111/1365-2745.12172

Márquez LM, Redman RS, Rodriguez RJ, Roossinck MJ (2007) A virus in a fungus in a plant: three-way symbiosis required for thermal tolerance. Science 315:513–515. https://doi.org/10.1126/science.1136237

Márquez S, Bills G, Zabalgogeazcoa I (2008) Diversity and structure of the fungal endophytic assemblages from two sympatric coastal grasses. Fungal Divers 33:87–100

Martiny JBH, Eisen JA, Penn K, Allison SD, Horner-Devine MC (2011) Drivers of bacterial beta-diversity depend on spatial scale. Proc Natl Acad Sci U S A 108:7850–7854. https://doi.org/10.1073/pnas.1016308108

Mayerhofer MS, Kernaghan G, Harper KA (2013) The effects of fungal root endophytes on plant growth: a meta-analysis. Mycorrhiza 23:119–128. https://doi.org/10.1007/s00572-012-0456-9

McKenzie RL, Aucamp PJ, Bais AF, Björn LO, Ilyas M, Madronich S (2011) Ozone depletion and climate change: impacts on UV radiation. Photochem Photobiol Sci 10:182–198. https://doi.org/10.1039/c0pp90034f

Meehl G, Stocker T, Collins W, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, JM M, Noda A, Raper S, Watterson IG, Weaver A, Zhao Z-C (2007) Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Cambridge University Press, New York, pp 747–845

Meinhardt KA, Gehring CA (2012) Disrupting mycorrhizal mutualisms: a potential mechanism by which exotic tamarisk outcompetes native cottonwoods. Ecol Appl 22:532–549. https://doi.org/10.1890/11-1247.1

Mercado LM, Medlyn BE, Huntingford C, Oliver RJ, Clark DB, Sitch S, Zelazowski P, Kattge J, Harper AB, Cox PM (2018) Large sensitivity in land carbon storage due to geographical and temporal variation in the thermal response of photosynthetic capacity. New Phytol 218:1462–1477. https://doi.org/10.1111/nph.15100

Mitchell CE, Power AG (2003) Release of invasive plants from fungal and viral pathogens. Nature 421:625–627. https://doi.org/10.1038/nature01317

Morse LJ, Faeth SH, Day TA (2007) Neotyphodium interactions with a wild grass are driven mainly by endophyte haplotype. Funct Ecol 21:813–822. https://doi.org/10.1111/j.1365-2435.2007.01285.x

Morsy MR, Oswald J, He J, Tang Y, Roossinck MJ (2010) Teasing apart a three-way symbiosis: transcriptome analyses of Curvularia protuberata in response to viral infection and heat stress. Biochem Biophys Res Commun 401:225–230. https://doi.org/10.1016/j.bbrc.2010.09.034

Nnadi NE, Carter DA (2021) Climate change and the emergence of fungal pathogens. PLoS Pathog 17:e1009503. https://doi.org/10.1371/journal.ppat.1009503

Oberhofer M, Güsewell S, Leuchtmann A (2014) Effects of natural hybrid and non-hybrid Epichloë endophytes on the response of Hordelymus europaeus to drought stress. New Phytol 201:242–253. https://doi.org/10.1111/nph.12496

Omacini M, Chaneton EJ, Ghersa CM, Müller CB (2001) Symbiotic fungal endophytes control insect host-parasite interaction webs. Nature 409:78–81. https://doi.org/10.1038/35051070

Pate FM, Snyder GH (1979) Effect of high water table in organic soil on yield and quality of forage grasses-Lysimeter study. Proc Soil Crop Sci Soc Fla 38:72–75

Peay KG, Garbelotto M, Bruns TD (2010) Evidence of dispersal limitation in soil microorganisms: isolation reduces species richness on mycorrhizal tree islands. Ecology 91:3631–3640. https://doi.org/10.1890/09-2237.1

Redman RS, Sheehan KB, Stout RG, Rodriguez RJ, Henson JM (2002) Thermotolerance generated by plant/fungal symbiosis. Science 298:1581. https://doi.org/10.1126/science.1072191

Reinhart KO, Packer A, Van der Putten WH, Clay K (2003) Plant–soil biota interactions and spatial distribution of black cherry in its native and invasive ranges. Ecol Lett 6:1046–1050. https://doi.org/10.1046/j.1461-0248.2003.00539.x

Rho H, Hsieh M, Kandel SL, Cantillo J, Doty SL, Kim S-H (2018) Do endophytes promote growth of host plants under stress? A meta-analysis on plant stress mitigation by endophytes. Microb Ecol 75:407–418. https://doi.org/10.1007/s00248-017-1054-3

Riess K, Oberwinkler F, Bauer R, Garnica S (2014) Communities of endophytic sebacinales associated with roots of herbaceous plants in agricultural and grassland ecosystems are dominated by Serendipita herbamans sp. nov. PLoS One 9:e94676. https://doi.org/10.1371/journal.pone.0094676

Rodriguez R, Redman R (2008) More than 400 million years of evolution and some plants still can't make it on their own: plant stress tolerance via fungal symbiosis. J Exp Bot 59:1109–1114. https://doi.org/10.1093/jxb/erm342

Rodriguez RJ, Henson J, Van Volkenburgh E, Hoy M, Wright L, Beckwith F, Kim Y-O, Redman RS (2008) Stress tolerance in plants via habitat-adapted symbiosis. ISME J 2:404–416. https://doi.org/10.1038/ismej.2007.106

Rodriguez RJ, White JF Jr, Arnold AE, Redman RS (2009) Fungal endophytes: diversity and functional roles. New Phytol 182:314–330. https://doi.org/10.1111/j.1469-8137.2009.02773.x

Rodriguez RJ, Woodward C, Redman RS (2010) Adaptation and survival of plants in high stress habitats via fungal endophyte conferred stress tolerance. In: Seckbach J, Grube M (eds) Symbioses and stress, cellular origin, life in extreme habitats and astrobiology. Springer, Dordrecht, pp 461–476. https://doi.org/10.1007/978-90-481-9449-0_23

Rudgers JA, Koslow JM, Clay K (2004) Endophytic fungi alter relationships between diversity and ecosystem properties. Ecol Lett 7:42–51. https://doi.org/10.1046/j.1461-0248.2003.00543.x

Rudgers JA, Mattingly WB, Koslow JM (2005) Mutualistic fungus promotes plant invasion into diverse communities. Oecologia 144:463–471. https://doi.org/10.1007/s00442-005-0039-y

Schoof JT, Pryor SC, Surprenant J (2010) Development of daily precipitation projections for the United States based on probabilistic downscaling. J Geophys Res Atmos 115. https://doi.org/10.1029/2009JD013030

Seager R, Ting M, Held I, Kushnir Y, Lu J, Vecchi G, Huang H-P, Harnik N, Leetmaa A, Lau N-C, Li C, Velez J, Naik N (2007) Model projections of an imminent transition to a more arid climate in Southwestern North America. Science 316:1181–1184. https://doi.org/10.1126/science.1139601

Shipunov A, Newcombe G, Raghavendra AKH, Anderson CL (2008) Hidden diversity of endophytic fungi in an invasive plant. Am J Bot 95:1096–1108. https://doi.org/10.3732/ajb.0800024

Solomon S, Intergovernmental Panel on Climate Change (eds) (2007) Climate change 2007: the physical science basis: contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge/New York

Stinson KA, Campbell SA, Powell JR, Wolfe BE, Callaway RM, Thelen GC, Hallett SG, Prati D, Klironomos JN (2006) Invasive plant suppresses the growth of native tree seedlings by disrupting belowground mutualisms. PLoS Biol 4:e140. https://doi.org/10.1371/journal.pbio.0040140

Tilman D, El Haddi A (1992) Drought and biodiversity in grasslands. Oecologia 89:257–264. https://doi.org/10.1007/BF00317226

Torres S, González-Ramírez M, Gavilán J, Paz C, Palfner G, Arnold N, Fuentealba J, Becerra J, Pérez C, Cabrera-Pardo JR (2019) Exposure to UV-B radiation leads to increased deposition of cell wall-associated xerocomic acid in cultures of Serpula himantioides. Appl Environ Microbiol 85:e00870–e00819. https://doi.org/10.1128/AEM.00870-19

US EPA, O (2022) Climate change indicators: atmospheric concentrations of greenhouse gases [WWW document]. https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases. Accessed 13 Aug 2022

van de Poll WH, Alderkamp A-C, Janknegt PJ, Roggeveld J, Buma AGJ (2006) Photoacclimation modulates excessive photosynthetically active and ultraviolet radiation effects in a temperate and an Antarctic marine diatom. Limnol Oceanogr 51:1239–1248. https://doi.org/10.4319/lo.2006.51.3.1239

van der Putten WH, Bardgett RD, Bever JD, Bezemer TM, Casper BB, Fukami T, Kardol P, Klironomos JN, Kulmatiski A, Schweitzer JA, Suding KN, Van de Voorde TFJ, Wardle DA (2013) Plant–soil feedbacks: the past, the present and future challenges. J Ecol 101:265–276. https://doi.org/10.1111/1365-2745.12054

Villafañe VE, Janknegt PJ, de Graaff M, Visser RJW, van de Poll WH, Buma AGJ, Walter Helbling E (2008) UVR-induced photoinhibition of summer marine phytoplankton communities from Patagonia. Mar Biol 154:1021–1029. https://doi.org/10.1007/s00227-008-0993-0

Vincent WF, Neale PJ (2000) Mechanisms of UV damage to aquatic organisms. In: De Mora S, Demers S, Vernet M (eds) The effects of UV radiation in the marine environment. Cambridge University Press, pp 149–176. https://doi.org/10.1017/CBO9780511535444.007

Waldrop MP, Firestone MK (2006) Response of microbial community composition and function to soil climate change. Microb Ecol 52:716–724. https://doi.org/10.1007/s00248-006-9103-3

Waller F, Achatz B, Baltruschat H, Fodor J, Becker K, Fischer M, Heier T, Hückelhoven R, Neumann C, von Wettstein D, Franken P, Kogel K-H (2005) The endophytic fungus Piriformospora indica reprograms barley to salt-stress tolerance, disease resistance, and higher yield. Proc Natl Acad Sci U S A 102:13386–13391. https://doi.org/10.1073/pnas.0504423102

Watson RT, Rodhe OH, Oeschger H, Siegenthaler U (1990) Greenhouse gases and aerosols. In: Houghton JT, Jenkins GJ, Ephraums JJ (eds) Climate change: the IPCC scientific assessment. Cambridge University Press

Watson RT, Meira Filho LG, Sanhueza E, Janetos A (1992) Greenhouse gases: sources and sinks. In: Houghton JT, Calander BA, Varney SK (eds) Climate change 1992. Supplementary report to the IPCC scientific assessment. Cambridge University Press, Cambridge

Way DA, Oren R (2010) Differential responses to changes in growth temperature between trees from different functional groups and biomes: a review and synthesis of data. Tree Physiol 30:669–688. https://doi.org/10.1093/treephys/tpq015

Way DA, Sage RF (2008) Thermal acclimation of photosynthesis in black spruce [*Picea mariana* (Mill.) B.S.P.]. Plant Cell Environ 31:1250–1262. https://doi.org/10.1111/j.1365-3040.2008.01842.x

Weiß M, Sýkorová Z, Garnica S, Riess K, Martos F, Krause C, Oberwinkler F, Bauer R, Redecker D (2011) Sebacinales everywhere: previously overlooked ubiquitous fungal endophytes. PLoS One 6:e16793. https://doi.org/10.1371/journal.pone.0016793

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, Bornman JF (2014) Solar ultraviolet radiation in a changing climate. Nat Clim Chang 4:434–441. https://doi.org/10.1038/nclimate2225

Wilson JR (1983) Effects of water stress on herbage quality, in: proceedings of the XIV international grassland congress. CRC Press

Wilson JR, Mannetje L (1978) Senescence, digestibility and carbohydrate content of buffel grass and green panic leaves in swards. Aust J Agric Res 29:503–516. https://doi.org/10.1071/ar9780503

Wilson JR, Ng TT (1975) Influence of water stress on parameters associated with herbage quality of Panicum maximum var. trichoglume. Aust J Agric Res 26:127–136. https://doi.org/10.1071/ar9750127

Wu X, Lu Y, Zhou S, Chen L, Xu B (2016) Impact of climate change on human infectious diseases: empirical evidence and human adaptation. Environ Int 86:14–23. https://doi.org/10.1016/j.envint.2015.09.007

Xu P, Chen F, Mannas JP, Feldman T, Sumner LW, Roossinck MJ (2008) Virus infection improves drought tolerance. New Phytol 180:911–921. https://doi.org/10.1111/j.1469-8137.2008.02627.x

Zhang H-N, Ma H-L, Zhou C-S, Yan Y, Yin X-L, Yan J-K (2016) Enhanced production and antioxidant activity of endo-polysaccharides from Phellinus igniarius mutants screened by low power He-Ne laser and ultraviolet induction. Bioact Carbohydr Diet Fibre 15:30–36. https://doi.org/10.1016/j.bcdf.2016.11.006