

The Impact of Heat Stress on Various Ecosystems and Crop Yields and the Response Strategies

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Abstract: Global warming-induced extremely high temperatures can cause irreversible impacts on the normal physiological processes of plants, such as photosynthesis and cell membrane fluidity, and may even lead to plant death. As an important component of ecosystems, plants are significantly affected by climate warming, which in turn has a far-reaching impact on the distribution and function of ecosystems and causes crop yield reduction, threatening food security. This paper summarizes the response patterns of forests and seagrass meadows at different latitudes to extreme high temperatures and the impact of climate warming on the yields of four major crops in their main producing areas. It is found that the impact of high temperature on different ecosystems varies with the type of ecosystem and shows differences in latitude, and global warming leads to varying degrees of yield reduction of the four major food crops in different producing areas. Moreover, the negative impact of high temperature on ecosystems also shows differences in the latitude distribution. Meanwhile, there are differences in the adaptability of different species to high temperatures. It is suggested that improving planting conditions and crop breeding may help combat the food security crisis caused by high temperatures.

Keywords: Global warming, Heat stress, Forest, Seagrass, Crop yield.

1. Introduction

Increasing greenhouse gas emissions caused by human activities, such as expanding urbanization, leads to an extremely rapid global warming. By the end of the 21st century, the global temperature was reported to rise by 1.1 to 6.4°C compared with the beginning of the 21st century [1]. Heatwaves, one of the main extreme climate events caused by global warming, can be defined as a climatic phenomenon with a daily maximum temperature higher than 32°C and lasting for more than three days [1]. Prolonged exposure to extremely high-temperature environments may cause serious damage to the physiological functions of animals and plants, and some species may suffer irreversible growth inhibition or death due to insufficient adaptability [2]. Plants grow in a fixed place and cannot actively choose a suitable environment, so they are affected more by climate change, which in turn affects the composition of the entire ecosystem and causes the loss of the function of ecosystems.

Different levels of high temperature will induce different responses in plants, and plants will also evolve adaptive mechanisms. Generally speaking, heat affects the physiological process of plants, leading to plant death, decreased immunity, and frequent insect outbreaks and diseases [3]. Structural changes such as hypocotyl elongation and altered flowering will happen when plants experience mild or moderate temperature increases, and such kind of response is called thermomorphogenesis. [4].

Severe high temperatures, however, will trigger heat stress and hurt plant growth and development, and may even lead to cell damage and death [5]. From a molecular point of view, heat stress mainly interferes with photosynthetic efficiency, respiratory enzyme activity, and the homeostasis of the plasma membrane, thereby interfering with the uptake of nutrients and intracellular signal transduction in plant cells, causing the production and accumulation of harmful substances within cells [4]. It should also be noted that crop production is extremely susceptible to significant temperature increases, which may lead to catastrophic crop yield losses [5, 6]. In summary, to deal with the inevitable threat of high temperature to ecosystem function and food security, it is necessary to explore the degree and mechanism of the impact of high temperature on the main plant groups in different ecosystems and food crops and to discuss response strategies.

Therefore, this article aims to explore the impact of extremely high temperatures on natural ecosystems represented by forests and seagrass meadows, as well as crops represented by wheat, rice, maize, and soybean in different latitudinal areas, then summarize methods to reduce crop yield losses.

2. The impact of high temperature on different types of ecosystems

Seagrass ecosystems and forest ecosystems provide habitats, food, and nursery areas for numerous vertebrate and invertebrate species and store most of the world's organic carbon, playing an important role in mitigating climate change. However, they are also suffering from the negative impacts of climate change.

2.1. The destruction of seagrass meadows by high temperature

Seagrass meadows are widely distributed in the temperate and tropical coastal areas of the world. Except for Antarctica, seagrass meadows grow along the coasts of all continents [7]. However, the global seagrass resources are rapidly shrinking.

Between 1993 and 2003, the total area of global seagrass meadows shrank by as much as 15% [7], and marine heatwaves are considered one of the main reasons for large-scale seagrass death. During the marine heatwave in 2010-2011, 36% of the seagrass in the world's largest seagrass meadow in the temperate region of the Southern Hemisphere was destroyed. This may lead to an increase in carbon emissions in the region by 9% to 21% in the next three years, thereby further exacerbating global warming [8]. In addition, the stress of heat waves on seagrass meadows in tropical regions cannot be ignored. Among the tropical marine seagrasses, when the water temperature reached to 39°C, the seagrass *Halodule wrightii* can survive after 120 hours of exposure, while *Thalassia hemprichii* can only withstand 48 hours exposure. However, when the exposure temperature reached 42°C, even the more heat-tolerant species of the genera *Halodule* and *Halophila* can survive after short-term exposure, long-term exposure to high temperatures will eventually lead to death [9]. Similarly, in the North Temperate Zone, due to heat stress, the southern distribution limit of the main seagrass species, eelgrass, in China has moved northward by 0.5 degrees over 70 years, and the transplantation and restoration carried out at the historical southern distribution limit, where in Rizhao, China, have completely failed, with no seedlings surviving after heat stress [10].

2.2. Forest distribution changes caused by high temperature

Forests account for 75% of the total primary productivity of terrestrial ecosystems [11]. However, in recent decades, many forest ecosystems have experienced forest decline and death due to climate change-driven disturbances. These disturbances include drought, pathogens, insect outbreaks, and wildfires, which can act individually or in combination with other factors, resulting in reduced tree growth and increased mortality rates. For example, physiological stress caused by drought has been proven to reduce the vitality of host trees, making them more susceptible to insect attacks [12].

In high-latitude areas, climate warming leads to increased drought and insect activity, causing the decline and withering of northern forests. Taking the trembling aspen forest in western Canada at 52° to 58°N as an example, from 1940 to 2010, among the 40 plots, 17 of them experienced insect outbreaks, which occurred in the 1960s, 1980s, and 2000s, while long-term and severe drought events occurred in the 1940s and 2000s [13]. Statistical results show that the decline in trembling aspen growth coincided with insect outbreaks, and both the climate moisture index and insect outbreaks had significant negative impacts on tree growth [13]. Meanwhile, researchers analyzed the 17 plots that had experienced insect outbreaks in detail and found that the average relative contributions of drought and insect outbreaks to forest decline were 78.81% and 21.19%, respectively. Therefore, the negative impact of drought on growth was greater than that of insect outbreaks. In addition, comparing plots in the southern to the northern parts of the forest, plots at higher latitudes were less affected by drought but more sensitive to insect outbreaks, while in the southern areas, the impact of drought increased to 86.8% [13].

Mangroves are a type of woody plant community distributed in the intertidal zones of tropical and subtropical regions (within the 16-25°C isotherm range), and their distribution is mainly affected by temperature, moisture, and sea level [10]. Unlike high-latitude forests, mangrove plants, also known as thermophilic plants, growing in low-latitude and low-altitude areas, may benefit from the expansion of their distribution boundaries to higher latitudes due to rising temperatures [14]. In China, if the temperature rises by 2°C, the natural northern boundary of mangroves is expected to expand northward by about 2.5 degrees of latitude, from approximately 27°N in Fujian to 29.5°N in Zhejiang [14]. However, the drought stress and sea level rise brought by climate warming can affect the normal flowering and fruiting time of mangrove plants, soil conditions, and community composition, thereby causing the decline of ecological functions and restricted expansion of mangroves. As early as 1997, researchers revealed that under waterlogged and low-water conditions, the growth parameters of *Rhizophora mangle* seedlings were 10%-20% lower than those of seedlings under normal conditions [15].

Table 1: Summary of the impact of high temperature on different ecosystems in different regions

Ecosystem type	species	Temperature zone	Latitude	Effect
Forest	Trembling aspen	Temperate	52-58°N	Insect outbreak, drought, reduced forest area, and slower tree growth.
Forest	Mangrove plants	Temperate	27°N	Short-term area increase: Northward expansion of 2.5 degrees/2°C. Changes in flowering rhythm and species composition
Seagrass meadow	Mixed seagrass	Temperate	25.5°S	36% of seagrass died within two years.
Seagrass meadow	<i>Halodule</i> , <i>Halophila</i> , <i>Thalassia</i> genus	Tropical	NA	Seagrass cannot survive in sustained heatwaves above 39°C.
Seagrass meadow	Eelgrass	Temperate	35.3°N	The southern boundary shifted northward by about 0.5 longitude over 70 years, restoration failure.

The impact of high temperature on different ecosystems in different areas is shown in Table 1. From Table 1, it can be preliminary concluded that although a slight short-term increase in temperature may have different effects on different ecosystems and may lead to an expansion of distribution area or faster growth, in the long term, heatwaves will have irreversible negative impacts on the functions and distribution areas of various ecosystems, and the degree of impact will vary with species characteristics and latitude. Generally speaking, ecosystems at high latitudes tend to show lower resistance to heat stress.

3. Global warming and food security

As an artificial community of plants, farmland is also affected by climate change and extreme high temperatures. The reduction in crop yields caused by high temperatures may pose a serious threat to global food security. Currently, wheat, rice, maize, and soybeans remain the world's major carbohydrate supply. Studies have shown that, without considering the CO₂ fertilization effect and genetic improvement, global wheat production will decrease by 6.0%, rice production by 3.2%, maize production by 7.4%, and soybean production by 3.1% when the global average temperature increase every 1°C[6]. Accurate estimation of the impact of climate on crop yield reduction and research on effective yield-increasing methods are crucial for mitigating the threat to food security.

The current mainstream methods for estimating the response of crop yields to climate change are fourfold: global and linear regional models based on the growth and development characteristics of crops [16,17], regression model analysis based on historical climate and yield data [18], and artificial warming experiments [19].

To summarize the impact of a 1°C increase in average annual temperature on the yields of the four major crops in different producing areas, literature data from the perspective of global warming and the yields of the four major crops (wheat, rice, maize, and soybean) were collected. Based on the collected data, the average yield changes of the four crops in the face of a 1°C temperature increase in some major producing areas can be estimated by calculating the average values of different estimation methods[20]. The results are shown in Table 2. For the four crops, a temperature increase in all major producing areas leads to varying degrees of yield loss, and the degree of loss is closely related to species characteristics and climatic conditions of the producing areas. Among them, the yields of wheat and rice in India are most severely affected by temperature, while the yields of maize and soybean decreased most in the United States.

Table 2: Average yield changes of wheat, rice, maize, and soybean in the world and major producing areas[6,16-19,21,22]

Wheat		Rice		Maize		Soybean	
Area	yield loss/°C	Area	yield loss/°C	Area	yield loss/°C	Area	yield loss/°C
India	9.1±5.4%	India	6.6±3.8%	India	5.2±4.5%	USA	6.8±7.1%
China	2.6±3.1%	China	3.70%	China	8.0±6.1%		
USA	5.5±4.4%			USA	10.3±5.4%		
France	6.0±4.2%			France	2.6±6.9%		
Russia	7.8±6.3			Brazil	5.5±4.5%		
Global	6.0±2.9%	Global	3.2±3.7%	Global	7.4±4.5%	Global	3.10%

These four methods use different data sources, time spans, and upscaling approaches [20], but the results of different methods consistently show that temperature hurts crop yields worldwide. Generally, different methods produce similar results at the national scale, while the results for different crops and geographical regions are highly heterogeneous [6, 20].

4. Suggestions and outlook

The differences in temperature response among different crop species worldwide indicate that different species have varying adaptability to high temperature, revealing the potential for breeding improvement in the face of the food security crisis caused by climate warming. Meanwhile, some mitigation measures, such as changing light exposure, fertilization, and water supplementation, may have a significant improvement in reducing the impact of climate change on agriculture. These

mitigation measures may be closely related to the nutritional environment of plants and the molecular mechanisms of temperature response. Scientists have currently proposed six strategies based on the physiological characteristics and growth processes of crops, called source strategies and sink strategies, revealing the direction of future breeding improvement, such as of potential mutation sites, and optimized planting conditions. From the perspective of the source, measures should be taken to protect photosynthesis, reduce water loss, and enhance the transport of nutrients and water during the growing period [4]. During the flowering and fruiting periods, three strategies from the sink perspective should be applied, including focusing on pollen vitality and sugar transport processes to maintain grain filling and appropriately supplementing fertilizers to avoid the accumulation of harmful substances [4].

5. Conclusion

This article analyzed the response of three typical seagrass ecosystems in the Southern Hemisphere temperate zone, tropical zone, and Northern Hemisphere temperate zone, and two typical forest ecosystems at high and low latitudes in the Northern Hemisphere to extremely high temperatures. The results show that high temperature has different impacts on different ecosystems, and the impact pattern varies with the type of ecosystem, while the degree of impact shows differences in latitude. A short-term increase in temperature may have a smaller negative impact on tropical and subtropical heat-tolerant plants and may even be beneficial for their northward expansion. However, long-term extreme climate has negative impacts on the functions and distribution areas of all ecosystems. Global warming leads to varying degrees of yield reduction of the four major food crops in different producing areas, with the most severe reduction in wheat and maize. Different prediction methods similarly indicate that different crops in different regions will experience yield reductions with differences. Finally, based on the growth characteristics of crops, six strategies to prevent yield reduction due to high temperature were summarized. During the growing period, it is necessary to protect photosynthesis, reduce water loss, and enhance the transport of nutrients and water. During the flowering and fruiting periods, it is important to focus on pollen vitality and grain filling processes and appropriately supplement fertilizers to avoid the accumulation of harmful substances.

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