Impacts of Summer Heat Waves and Increasing Temperatures on Agriculture

Summary

This report provides an analysis of the implications of rising temperatures and heat waves on agriculture and the farming community. In recent years, we have been experiencing an increased occurrence of heat waves and drought, which can have negative impacts on agricultural production, the agricultural economy, and local and state economies. We discuss how heat affects stages of crop growth, yields and regional economies, and highlight new mitigation strategies for the future.

Introduction

Steady increases in average temperatures and extreme weather patterning have been observed over the past 20 years. Heat waves of increasing intensity and duration are predicted, leading to worsening drought conditions (Dettinger et al., 2015). Heat waves are detrimental to agriculture, leading not only to drought, but also to heat stress and crop yield losses. Weather extremes negatively affect the agricultural industry. Plants under high heat conditions tend to have reduced water use efficiency, which can trigger desiccation, wilting, reduced fertility, reduced yields, and eventual death of the plant (Perera et al., 2019; Bailey-Serres et al., 2019). Rising temperatures can also increase the duration of droughts. Cereal and vegetable crops are at risk of reduced yields in response to heat stress, thus straining the agricultural economy. Under current trends both corn (maize) and soybeans are predicted to show reduced yields, the effects of which can already be found in Europe and are expected to spread and worsen over time (Perera et al., 2019; Zhao et al., 2017). With the effects of increasing temperatures, the threat to food production and security will remain high unless losses to stresses can be minimized (Fodor et al., 2017). Agriculture is predicted to be the most negatively impacted industry resulting from rising temperatures and the accompanying challenges (Raza et al., 2019). In this article, we review the specific mechanisms throughout the life cycle of plants that are most vulnerable to crop productivity and discuss present and future economic impacts of heat stress in agriculture and possible mitigation strategies.

Heat Waves

The average global temperature has risen 0.8-1.2°C (2.2°F) in the last 100 years, which is beginning to affect extreme weather events (Jia et al.2019). Over two thirds of this warming has occurred in the last 44 years, with recent decades setting numerous new annual record high global temperatures (Abatzoglou et al., 2014; Vose et al., 2017). Over the previous 140 years, the last five years have been the hottest on record (Brown et al., 2020). This increase is correlated with a global increase in occurrences of drought, expanding deserts, heat waves, wildfires and flooding (Jia et al., 2019; Yuan et al., 2019).

Figure 1: *Decimation of crops is a catastrophic side effect of heat waves. Corn, shown here, is just one of many food crops that are affected. Source: iStock.*

The global temperature increase is resulting in hotter summers and shorter, warmer winters (Jia et al., 2019). This trend will continue to contribute to extreme weather events (Dahl et al., 2019). Heat waves with lessened cooler nighttime temperatures are expected to increase in frequency, intensity, and duration. In the absence of nighttime cooling, crops will not have essential relief from daytime heat, resulting in yield losses (Sadok et al., 2020).

Heat waves also have a direct impact on human life. An example would be the 2003 heat wave in Europe, which caused approximately 30,000 deaths, 14,000 of which occurred in France alone. Already, there has been an unprecedented increase in the number of heat-related deaths in the southwestern US, with the number of deaths tripling in Arizona and quintupling in Nevada between 2014 and 2017 (Flavelle et al., 2019). Such extreme weather events will result in increased deaths of a myriad of species, beginning with numerous plant species, due to the combined heat and drought.

Critical to US agriculture, these heat waves are occurring more often in North America. Specifically, extreme heat waves in recent years have occurred in the southwest, west, mid-west, and southeastern US (Jia et al., 2019). This increased prevalence of heat waves will have a negative impact on crop plants (Irmak, 2016). In one example, the 2010 heat wave in Russia decimated 25% of the season's wheat crops with losses topping $12 billion (Cullen and Tebaldi, 2010). These heat events are important to consider for their predicted long-term prevalence, as well as the increasing frequency and intensity.

Recent wildfires have been predicted to result from the upwards trends in temperatures and occurrence of heat waves. According to fire researcher Mike Flannigan: "In Canada, the area burnt by wildfires has doubled since 1970. They previously burnt around 2.5 million acres a year. ...now we have been averaging more than 6.1 million acres a year" (equivalent to the area of Vermont) ... "In the western US, the area burnt has actually quadrupled since the 1970s..." (Dimitropoulos et al., 2019). The fatal California fires of 2018, the deadliest in the state's history, caused widespread deaths and cost the state over $3.5 billion in damages (National Interagency Fire Center). The 2020 wildfires in the western U.S. were the largest in recorded history with over 12 million acres burned. Similar to recent trends in the U.S., the 2019-20 Australian bushfires began sooner than the expected fire season, caused by drought and heat, and led to the destruction of over 25 million acres of forests and field crops (Yeung et al., 2020).

Desertification

Increased temperatures, heat waves, and desertification of viable farmland are proving to be a significant threat to agricultural production (Yuan et al., 2019). Desertification refers to the conversion of an environment to a desert-like landscape, resulting from the culmination of biological, chemical, and physical processes (Mainguet et al., 1998). Desertification is remarkably difficult to revert. Some symptoms include changes in soil dynamics of organic matter decomposition, leaching, and soil degradation (Sivakumar et al., 2007). Soil degradation can further enhance the damaging effects of excessive heat and decrease overall crop yields by as much as 16% due to reductions in seed germination, seedling establishment, and plant cover (Mainguet et al., 1998; Sivakumar et al., 2007). Complications caused by land desertification are already occurring in the Southwestern US. When applied to the US heartland, it is predicted that aridity, on par with that of the US dust bowls of the 1930s, may affect the US west of Iowa and Missouri over the next 30 years (Romm, 2011).

***Figure 2**: Heat stress is causing severe droughts, and is ravaging crops. Photo by Dwight Seaggreen.*

Impact of Heat: Plant Biological Mechanisms

High temperatures, together with drought stress, negatively affect food crops. The combination of heat and drought stresses can disrupt seedling germination, vegetative growth, tiller production, dry matter partitioning, reproductive organ development, pollen tube growth, fertilization, grain filling, and grain quality (Sehgal et al., 2018, Bailey-Serres et al., 2019). Heat waves cause reduced photosynthetic rates, early leaf senescence, and inefficient water usage in food crops and other plants (Sehgal et al., 2018). Heat waves can also decimate crop yields by destabilizing key proteins required for plant growth. For example, Ribulose-1,5-bisphosphatecarboxylase/oxygenase (RuBis-Co), the most abundant protein on earth, is a crucial protein because it catalyzes the rate-limiting step of CO_2 fixation in photosynthesis, thus enabling plant growth (Spreitzer et al., 2003). Heat stress caused by heat waves can reduce the activity of RuBisCo, leading to inhibition of plant growth and reduced crop yields (Figures 1 & 2) by limiting photosynthetic activity. A critical stage that determines grain yield is grain filling. Notably, although high temperatures can accelerate the rate of seed filling, they can also reduce the duration of this stage, causing a reduction in overall seed filling and negatively impacting yield (Sehgal et al., 2018).

As stationary organisms, plants have evolved multiple mechanisms that allow them to overcome heat stress. Stomatal pores are tiny pores on the surface of leaves that regulate evapotranspiration and CO_2 intake into leaves needed for photosynthesis. Moreover, stomatal pores are a key component in protection against heat, as they enable cooling of leaves by allowing water loss via transpiration. The continuing steep rise in the atmospheric CO_2 concentration is not only warming the planet, but this elevated CO_2 is also a signal that triggers narrowing of stomatal pores (Bailey-Serres et al., 2019). This reduces water transpiration from leaves, further increasing leaf temperatures and heat stress. Increased soil drying due to more extreme heat waves directly affects plant transpiration. Dry soils combined with transpirational water loss of plants leads to cavitation, which refers to air spaces or embolisms in the xylem vessels that carry water from plant roots to leaves (Choat et al., 2018). This cavitation in xylem vessels is particularly critical for trees, leading to tree mortality and subsequent increased fire danger in response to combined heat and drought (Choat et al., 2018). Furthermore, when water becomes scarce, stomatal pores in leaves close, which in turn further compounds heat stress in leaves. Thus, heat stress can affect multiple stages of plant growth beginning from germination until maturity.

Figure 3: *Crop yields are stunted by heat stress and drought. Source: Shutterstock.*

Heat and Pollinators

Another current pressing threat to agricultural production is the decrease in insect pollinators. Bee populations have declined in the US and Europe, with increasing temperatures thought to be one of the contributing factors. Heat waves are altering the flowering times of many different species of plants that are dependent on bee pollinators. Approximately one-third of agriculture relies on bee pollination, therefore loss or reduced pollination activity by bees could be highly detrimental, causing crop yields to fall (Giannini et al., 2012). Beyond their impact on agriculture, bees are a keystone species in most ecosystems.

Agricultural Revenue

In addition to the direct effects of heat stress on plant productivity, there are immense financial and economic repercussions for farmers and other businesses that rely heavily on prime farming conditions for their livelihoods. As early as 1998, the Texas drought caused revenue losses of $2.1 billion for producers alone, leaving the state with a $5.7 billion loss in total revenue. One of the greatest losses in revenue in the US due to heat and drought stress was the intense Midwestern drought of 2012, considered to be as costly as Hurricane Sandy. This led to an estimated $75 to $150 billion in revenue losses (Freedman et al., 2012). Deutsche Bank Securities estimated a one-point drop in US gross domestic product (GDP) due to the severity of the 2012 Midwestern drought. These losses, though large, were smaller than initially predicted likely due to no-till farming, which aids in trapping soil moisture, and introduction of first generation more drought tolerant maize varieties.

Heat negatively affects the agricultural economy and farmers. As a result, the effects of increasing atmospheric CO_2 concentration and the resulting heatwaves can become a national economic problem. Temperature increases will have unequal effects on certain regions of the world, including negative impacts on the Western and Midwestern US (Burke et al., 2015). Worldwide, as the planet warms, countries closer to the equator are more at risk in terms of their agricultural GDP. In one analysis, the US is predicted to experience a 36% GDP decrease. Thus, overall losses in GDP due to heat stress are both a regional and national issue (Burke et al., 2015).

Mitigation Strategies

A number of approaches are being pursued and investigated in engineering and research. Engineering approaches are pursing avenues to enhance water availability, since this can help cool crops. These include subterranean drip irrigation, recycling water and attempts to replenish ground water during rain periods. In Israel, for example, subterranean drip irrigation is widely used, which also helps keep crops cool and approximately 90% of water is recycled, resulting in enhanced yields despite heat and water scarcity. By contrast, about 0.3% of water is recycled in the U.S. with much room for engineering solutions.

On the crop research side, the genomic revolution is leading to advanced breeding and molecular engineering approaches, including introgression of genetic traits for heat resistance from wild relatives of high-yielding crops. However, more research is needed to understand the mechanisms and genes that enhance resilience of crops to heat stress. The tools for this relevant research have never been more powerful. The genomics revolution is further adding important new research towards identifying soil microbes that are beneficial and aid in enhancing heat stress resistance of crops. Research on the above-described CO_2 regulation of plant water loss via stomatal pores, is leading to new strategies for enhancing the water use efficiency of crops, which itself could contribute to reduction in plant desiccation, soil drying and ground water depletion. New powerful research tools as well as scientists are primed for developing new approaches for enhancing yields in light of the prospect of increased summer heat waves.

Conclusions

The heat-trapping nature of CO_2, coupled with the continuing steep increase in its atmospheric concentration, has resulted in increased global temperatures. Heat waves, flooding, droughts, and fires threaten communities and local and state economies by damaging crops, while threatening farming. Present data suggest that heat waves are occurring at increasing rates and further increased temperatures are predicted to have unprecedented negative effects on agriculture, with the impact of this increase already being felt in some regions. A combination of engineering and new scientific discoveries, aided by previously unavailable powerful research tools provides an opportunity to tackle the underlying issues towards securing the future of agriculture and is crucial to maintaining farming communities, lives and livelihoods, as we currently know them.

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