



- Many crops show positive responses to elevated carbon dioxide and low levels of warming, but higher levels of warming often negatively affect growth and yields.
- Extreme events such as heavy downpours and droughts are likely to reduce crop yields because excesses or deficits of water have negative impacts on plant growth.
- Weeds, diseases, and insect pests benefit from warming, and weeds also benefit from a higher carbon dioxide concentration, increasing stress on crop plants and requiring more attention to pest and weed control.
- Forage quality in pastures and rangelands generally declines with increasing carbon dioxide concentration because of the effects on plant nitrogen and protein content, reducing the land's ability to supply adequate livestock feed.
- Increased heat, disease, and weather extremes are likely to reduce livestock productivity.

Crop responses in a changing climate reflect the interplay among three factors: rising temperatures, changing water resources, and increasing carbon dioxide concentrations. Warming generally causes plants that are below their optimum temperature to grow faster, with obvious benefits. For some plants, such as cereal crops, however, faster growth means there is less time for the grain itself to grow and mature, reducing yields.¹⁹³ For some annual crops, this can be compensated for by adjusting the planting date to avoid late season heat stress.¹⁶⁴

The grain-filling period (the time when the seed grows and matures) of wheat and other small grains shortens dramatically with rising temperatures. Analysis of crop responses suggests that even moderate increases in temperature will decrease yields of corn, wheat, sorghum, bean, rice, cotton, and peanut crops.¹⁹³

Some crops are particularly sensitive to high nighttime temperatures, which have been rising even faster than daytime temperatures.⁶⁸ Nighttime temperatures are expected to continue to rise in the future. These changes in temperature are especially critical to the reproductive phase of growth because warm nights increase the respiration rate and reduce the amount of carbon that is captured during the day by photosynthesis to be retained in

the fruit or grain. Further, as temperatures continue to rise and drought periods increase, crops will be more frequently exposed to temperature thresholds at which pollination and grain-set processes begin to fail and quality of vegetable crops decreases. Grain, soybean, and canola crops have relatively low optimal temperatures, and thus will have reduced yields and will increasingly begin to experience failure as warming proceeds.¹⁹³ Common snap beans show substantial yield reduction when nighttime temperatures exceed 80°F.

Higher temperatures will mean a longer growing season for crops that do well in the heat, such as melon, okra, and sweet potato, but a shorter growing season for crops more suited to cooler conditions, such as potato, lettuce, broccoli, and spinach.¹⁹³ Higher temperatures also cause plants to use more water to keep cool. This is one example of how the interplay between rising temperatures and water availability is critical to how plants respond to climate change. But fruits, vegetables, and grains can suffer even under well-watered conditions if temperatures exceed the maximum level for pollen viability in a particular plant; if temperatures exceed the threshold for that plant, it won't produce seed and so it won't reproduce.¹⁹³

Temperature increases will cause the optimum latitude for crops to move northward; decreases in temperature would cause shifts toward the equator. Where plants can be efficiently grown depends upon climate conditions, of which temperature is one of the major factors.


Corn and Soybean Temperature Response



For each plant variety, there is an optimal temperature for vegetative growth, with growth dropping off as temperatures increase or decrease. Similarly, there is a range of temperatures at which a plant will produce seed. Outside of this range, the plant will not reproduce. As the graphs show, corn will fail to reproduce at temperatures above 95°F and soybean above 102°F.

Plants need adequate water to maintain their temperature within an optimal range. Without water for cooling, plants will suffer heat stress. In many regions, irrigation water is used to maintain adequate temperature conditions for the growth of cool season plants (such as many vegetables), even in warm environments. With increasing demand and competition for freshwater supplies, the water needed for these crops might be increasingly limited. If water supply variability increases, it will affect plant growth and cause

Ground-level ozone (a component of smog) is an air pollutant that is formed when nitrogen oxides emitted from fossil fuel burning interact with other compounds, such as unburned gasoline vapors, in the atmosphere,²³⁷ in the presence of sunlight. Higher air temperatures result in greater concentrations of ozone. Ozone levels at the land surface have risen in rural areas of the United States over the past 50 years, and they are forecast to continue increasing with warming, especially under higher emissions scenarios.⁹¹ Plants are sensitive to ozone, and crop yields are reduced as ozone levels increase. Some crops that are particularly sensitive to ozone pollution include soybeans, wheat, oats, green beans, peppers, and some types of cotton.¹⁹³



damage. Mild winters and warm, early springs, which are beginning to occur more frequently as climate warms, induce premature plant development and blooming, resulting in exposure of vulnerable young plants and plant tissues to subsequent late-season frosts. For example, the 2007 spring freeze in the eastern United States caused widespread devastation of crops and natural vegetation because the frost occurred during the flowering period of many trees and during early grain development on wheat plants.²³⁵ Another example is occurring in the Rocky Mountains where in addition to the process described above, reduced snow cover leaves young plants unprotected from spring frosts, with some plant species already beginning to suffer as a result²³⁶ (see *Ecosystems* sector).

stage, inundating hundreds of thousands of acres of cropland. The flood hit just as farmers were preparing to harvest wheat and plant corn, soybeans, and cotton. Preliminary estimates of agricultural losses are around \$8 billion.²¹³ Some farmers were put out of business and others will be recovering for years to come. The flooding caused severe erosion in some areas and also caused an increase in runoff and leaching of agricultural chemicals into surface water and groundwater.²³³

Another impact of heavy downpours is that wet conditions at harvest time result in reduced quality of many crops. Storms with heavy rainfall often are accompanied by wind gusts, and both strong winds and rain can flatten crops, causing significant damage. Vegetable and fruit crops are sensitive to even short-term, minor stresses, and as such are par-

deficits of water have negative impacts

One of the most pronounced effects of climate change is the increase in heavy downpours. Precipitation has become less frequent but more intense, and this pattern is projected to continue across the United States.¹¹² One consequence of excessive rainfall is delayed spring planting, which jeopardizes profits for farmers paid a premium for early season production of high-value crops such as melon, sweet corn, and tomatoes. Field flooding during the growing season causes crop losses due to low oxygen levels in the soil, increased susceptibility to root diseases, and increased soil compaction due to the use of heavy farm equipment on wet soils. In spring 2008, heavy rains caused the Mississippi River to rise to about 7 feet above flood

ticularly vulnerable to weather extremes.¹⁹³ More rainfall concentrated into heavy downpours also increases the likelihood of water deficiencies at other times because of reductions in rainfall frequency.

Drought frequency and severity are projected to increase in the future over much of the United States, particularly under higher emissions scenarios.^{90,91} Increased drought will be occurring at a time when crop water requirements also are increasing due to rising temperatures. Water deficits are detrimental for all crops.²³³

Temperature extremes will also pose problems. Even crop species that are well-adapted to warmth, such as tomatoes, can have reduced yield and/or quality when daytime maximum temperatures exceed 90°F for even short periods during critical reproductive stages (see maps page 34).¹¹² For many high-value crops, just hours or days of moderate heat stress at critical growth stages can reduce grower profits by negatively affecting visual or flavor quality, even when total yield is not reduced.²³⁸

benefit from warming, and weeds also benefit from a higher carbon dioxide

Weeds benefit more than cash crops from higher temperatures and carbon dioxide levels.¹⁹³ One concern with continued warming is the northward expansion of invasive weeds. Southern farmers currently lose more of their crops to weeds than do northern farmers. For example, southern farmers lose 64 percent of the soybean crop to weeds, while northern farmers lose 22 percent.²³⁹ Some extremely aggressive weeds plaguing the South (such as kudzu) have historically been confined to areas where winter temperatures do not drop below specific thresholds. As temperatures continue to rise, these weeds will expand their ranges northward into important ag-

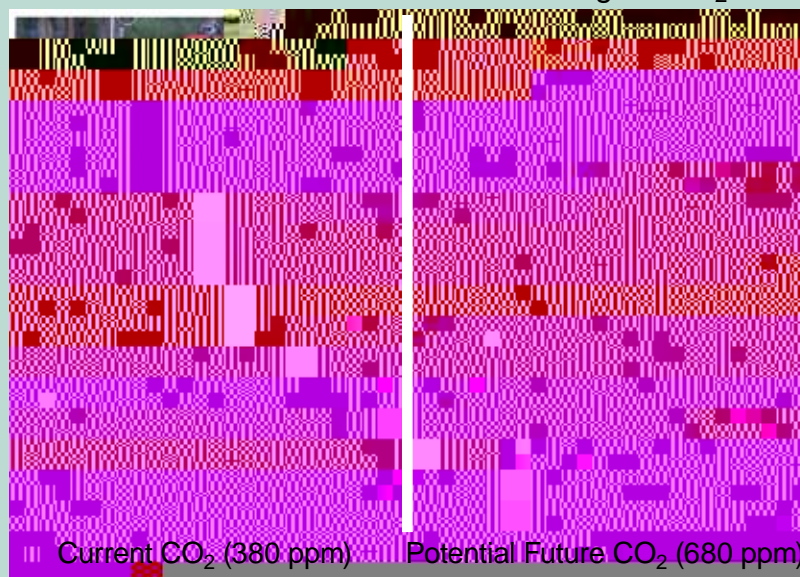
ricultural areas.²⁴⁰ Kudzu currently has invaded 2.5 million acres of the Southeast and is a carrier of the fungal disease soybean rust, which represents a major and expanding threat to U.S. soybean production.²³⁴

Controlling weeds currently costs the United States more than \$11 billion a year, with the majority spent on herbicides;²⁴¹ so both herbicide use and costs are likely to increase as temperatures and carbon dioxide levels rise. At the same time, the most widely used herbicide in the United States, glyphosate (RoundUp®), loses its efficacy on weeds grown at carbon dioxide levels that are projected to occur in the coming decades (see photos below). Higher concentrations of the chemical and more frequent spraying thus will be needed, increasing economic and environmental costs associated with chemical use.²³³

Many insect pests and crop diseases thrive due to warming, increasing losses and necessitating greater pesticide use. Warming aids insects and diseases in several ways. Rising temperatures allow both insects and pathogens to expand their ranges northward. In addition, rapidly rising winter temperatures allow more insects to survive over the winter, whereas cold winters once controlled their populations. Some of these insects, in addition to directly



Herbicide Loses Effectiveness at Higher CO₂



The left photo shows weeds in a plot grown at a carbon dioxide (CO₂) concentration of about 380 parts per million (ppm), which approximates the current level. The right photo shows a plot in which the CO₂ level has been raised to about 680 ppm. Both plots were equally treated with herbicide.²³³

damaging crops, also carry diseases that harm crops. Crop diseases in general are likely to increase as earlier springs and warmer winters allow proliferation and higher survival rates of disease pathogens and parasites.^{193,234} The longer growing season will allow some insects to produce more generations in a single season, greatly increasing their populations. Finally, plants grown in higher carbon dioxide conditions tend to be less nutritious, so insects must eat more to meet their protein requirements, causing greater destruction to crops.¹⁹³

Due to the increased presence of pests, spraying is already much more common in warmer areas than in cooler areas. For example, Florida sweet corn growers spray their fields 15 to 32 times a year to fight pests such as corn borer and corn earworm, while New York farmers average zero to five times.¹⁹³ In addition, higher temperatures are known to reduce the effectiveness of certain classes of pesticides (pyrethroids and spinosad).

A particularly unpleasant example of how carbon dioxide tends to favor undesirable plants is found in the response of poison ivy to rising carbon dioxide concentrations. Poison ivy thrives in air with extra carbon dioxide in it, growing bigger and producing a more toxic form of the oil, urushiol, which causes painful skin reactions in 80 percent of people. Contact with poison ivy is one of the most widely reported ailments at poison centers in the United States, causing more than 350,000 cases of contact dermatitis each year. The growth stimulation of poison ivy due to increasing carbon dioxide concentration exceeds that of most other woody species. Given continued increases in carbon dioxide emissions, poison ivy is expected to become more abundant and more toxic in the future, with implications for forests and human health.²³⁴

Higher temperatures, longer growing seasons, and increased drought will lead to increased agricultural water use in some areas. Obtaining the maxi-

imum “carbon dioxide fertilization” benefit often requires more efficient use of water and fertilizers that better synchronize plant demand with supply. Farmers are likely to respond to more aggressive and invasive weeds, insects, and pathogens with increased use of herbicides, insecticides, and fungicides. Where increases in water and chemical inputs become necessary, this will increase costs for the farmer, as well as having society-wide impacts by depleting water supply, increasing reactive nitrogen and pesticide loads to the environment, and increasing risks to food safety and human exposure to pesticides.



not seeded and receive much less rainfall. There are



amount of water plants use and water availability over time and space. The ability to anticipate vegetation changes at local scales and over shorter periods is limited because at these scales the response of vegetation to global-scale changes depends on a variety of local processes including the rate of disturbances such as fire and grazing, and the rate at which plant species can move across sometimes-fragmented landscapes. Nevertheless, some general patterns of vegetation change are beginning to emerge. For example, experiments indicate that a higher carbon dioxide concentration favors weeds and invasive plants over native species because invasives have traits (such as rapid growth rate and prolific seed production) that allow a larger growth response to carbon dioxide. In addition, the effect of a higher carbon dioxide concentration on plant species composition appears to be greatest where the land has been disturbed (such as by fire or grazing) and nutrient and light availability are high.¹⁹³

Increases in temperature lengthen the growing season, and thus are likely to extend forage production into the late fall and early spring. However, overall productivity remains dependent on precipitation during the growing season.¹⁹³

Like human beings, cows, pigs, and poultry are warm-blooded animals that are sensitive to heat. In terms of production efficiency, studies show that the negative effects of hotter summers will outweigh the positive effects of warmer winters. The more the U.S. climate warms, the more production will fall. For example, an analysis projected that a warming in the range of 9 to 11°F (as in the higher emissions scenarios⁹¹) would cause a 10 percent decline in livestock yields in cow/calf and dairy operations in Appalachia, the Southeast (including the Mississippi Delta), and southern Plains regions, while a warming of 2.7°F would cause less than a 1 percent decline.

Temperature and humidity interact to cause stress in animals, just as in humans; the higher the heat and humidity, the greater the stress and discomfort,

and the larger the reduction in the animals' ability to produce milk, gain weight, and reproduce. Milk production declines in dairy operations, the number of days it takes for cows to reach their target weight grows longer in meat operations, conception rate in cattle falls, and swine growth rates decline due to heat. As a result, swine, beef, and milk production are all projected to decline in a warmer world.¹⁹³

The projected increases in air temperatures will negatively affect confined animal operations (dairy, beef, and swine) located in the central United States, increasing production costs as a result of reductions in performance associated with lower feed intake and increased requirements for energy to maintain healthy livestock. These costs do not account for the increased death of livestock associated with extreme weather events such as heat waves. Nighttime recovery is an essential element of survival when livestock are stressed by extreme heat. A feature of recent heat waves is the lack of nighttime relief. Large numbers of deaths have occurred in recent heat waves, with individual states reporting losses of 5,000 head of cattle in a single heat wave in one summer.¹⁹³

Warming also affects parasites and disease pathogens. The earlier arrival of spring and warmer winters allow greater proliferation and survival of parasites and disease pathogens.¹⁹³ In addition, changes in rainfall distributions are likely to lead to changes in diseases sensitive to moisture. Heat stress reduces animals' ability to cope with other stresses, such as diseases and parasites. Furthermore, changes in rainfall distributions could lead to changes in diseases sensitive to relative humidity.

Maintaining livestock production would require modifying facilities to reduce heat stress on animals, using the best understanding of the chronic and acute stresses that livestock will encounter to determine the optimal modification strategy.¹⁹³

Changing livestock species as an adaptation strategy is a much more extreme, high-risk, and, in most cases, high-cost option than changing crop varieties. Accurate predictions of climate trends and development of the infrastructure and market for the new livestock products are essential to making this an effective response.

