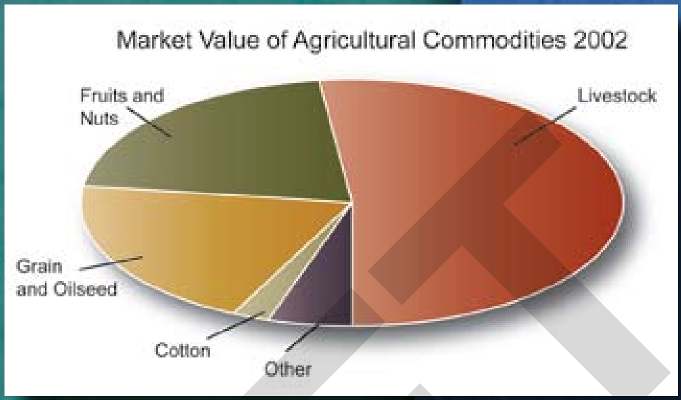
Agriculture and

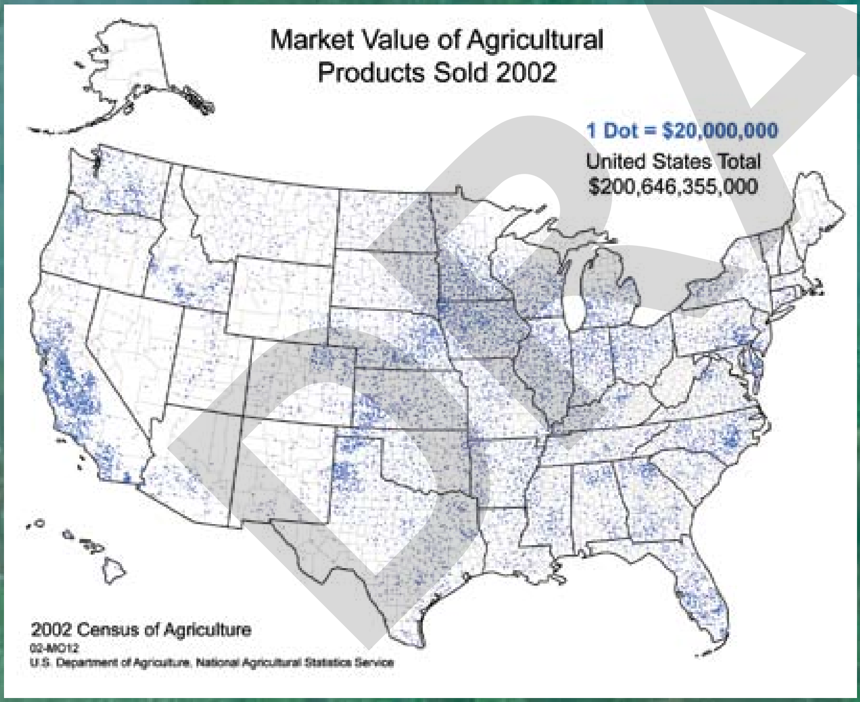
- Crops show mixed responses to lower levels of warming, but higher levels of warming often negatively affect growth and yields.
- Extreme events such as heavy downpours and droughts reduce crop yields.
- Weeds, diseases, and insect pests benefit from warming, and weeds also benefit from rising carbon dioxide (CO_2), increasing stress on crop plants and requiring more pesticide and herbicide use.
- Forage quality in pasture and rangeland generally declines, reducing the land's ability to supply adequate livestock feed.
- Increased heat, disease, and weather extremes reduce livestock productivity.
- Warming and rising CO_2 increase forest growth, but more insect outbreaks, fire, and drought have negative effects.
- Deserts and dry lands become hotter and drier, feeding a self-reinforcing cycle of invasive plants, fire, and erosion.

Land Resources

Agriculture in the United States is extremely diverse and produces over $200 billion a year in food commodities. The impacts of climate change on agriculture will also be very diverse, varying by region and by product[1].



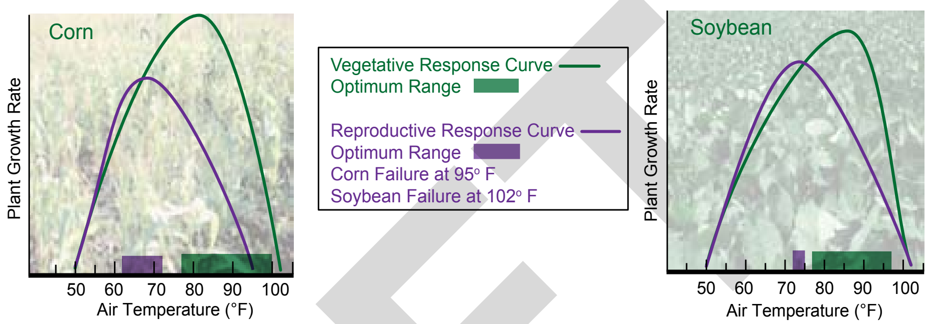
While climate change clearly impacts agriculture, agriculture also impacts climate, contributing 13.5 percent of all human-induced greenhouse gas emissions globally. In the U.S., agriculture represents 8.6 percent of the nation's total greenhouse gas emissions, including 80 percent of its nitrous oxide emissions and 31 percent of its methane emissions[2].



Crops show mixed responses to lower levels of warming, but higher levels of warming often negatively affect growth and yields.

Crop responses in a changing climate reflect the interplay among three factors: rising temperatures, increasing carbon dioxide concentrations, and changing water resources. Warming causes plants to grow faster, which is not necessarily a good thing, as this means there is less time for the grain to "fill" in cereal crops, reducing their yields[3].

Higher carbon dioxide levels cause plants to grow bigger; again, this is not necessarily a good thing as they are also generally less nutritious with reduced protein content. Carbon dioxide also makes some plants more water-use-efficient, meaning they produce more plant material, such as grain, on less water[4].



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 most vegetables), even in warm environments. With increasing demand and competition for fresh water supplies, the water needed for these crops may be increasingly limited. Variability in the water supply will affect plant growth and cause drastically reduced yields. The amount and timing of precipitation during the growing season are also critical, and will be affected by climate change. Changes in season length are also important and affect crops differently[5].

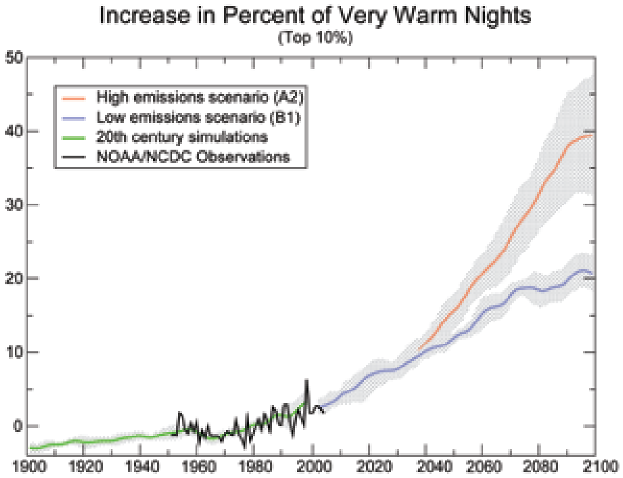
Higher temperatures will mean a longer growing season for crops that do well in the heat, such as melon, okra, and sweet potato, but a shorter growing season for crops more suited to cooler conditions, such as potato, lettuce, broccoli, and spinach[6]. Higher temperatures also cause plants to use more 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[7].

The grain-filling period 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. 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 is negatively affected. 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[8].

Some crops are particularly sensitive to high nighttime temperatures, which have been rising even faster than daytime temperatures and are projected to continue to do so[9]. Common snap beans, for example, shows substantial yield reduction when nighttime temperatures exceed 80°F.

Fruits that require long winter chilling periods will suffer declines. Many varieties of fruits (such as popular varieties of apples and berries) require between 400 and 1800 cumulative hours below 45°F each winter to produce good yields the following summer and fall. By late this century, under higher emissions scenarios, winter temperatures in many important fruit-producing regions such as the Northeast will be too consistently warm to meet these requirements. Cranberries have a particularly high chilling requirement and there are no known low-chill varieties. Massachusetts and New Jersey supply nearly half the nation's cranberry crop. By the middle of this century, under higher emissions scenarios, it is unlikely that these areas will provide cranberries with the winter chilling they need[10].

A seemingly paradoxical impact of warming is that it appears to be increasing the risk of plant frost 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[11]. 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 result[12] (see *Ecosystems* sector).



Change in percent of very warm nights from the 1950 to 1990 average. Under the lower emissions scenario, the percentage of very warm nights increases about 20 percent by 2100 whereas under the higher emissions scenario, it increases by about 40 percent[9].

Effects of increased air pollution on crop yields

Ground-level ozone is an air pollutant that is formed when nitrogen oxides emitted from fossil fuel burning interact with other compounds in the atmosphere[12a] in the presence of sunlight. Higher air temperatures result in greater concentrations of ozone. Ozone at the land surface has risen in rural areas of the United States over the past 50 years, and it is forecast to continue increasing with warming, especially under higher emissions scenarios. 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[13].

Extreme events such as heavy downpours and droughts reduce crop yields.

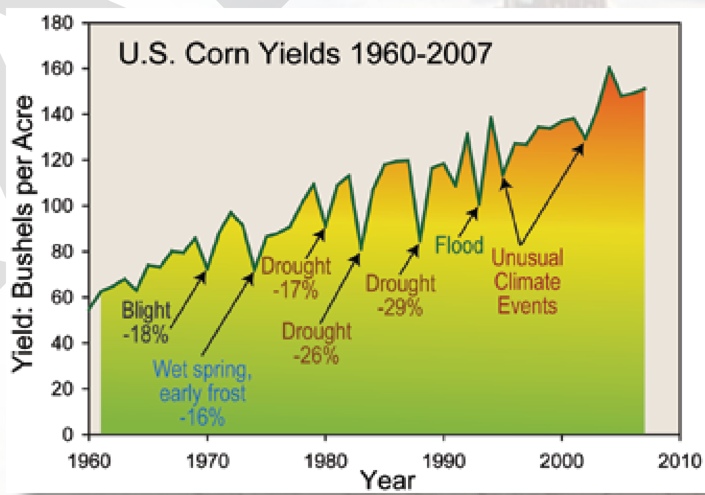
One of the most pronounced effects of climate change is the increase in heavy downpours. Precipitation has become less frequent but more intense, and this pattern is projected to continue across the United States[14]. One consequence of excessive rainfall is delayed spring planting, which jeopardizes 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 conditions, 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 seven feet above flood stage, putting hundreds of thousands of acres of cropland under water. The flood hit just as farmers were preparing to harvest wheat and to plant corn, soybeans and cotton. The losses have not yet been estimated but are expected to be large, requiring years of recovery time and even putting some farmers out of business. The flooding also caused an increase in runoff and leaching of agricultural chemicals into surface water and groundwater[15].

Vegetable and fruit crops are sensitive to even short-term, minor stresses, and as such are vulnerable to weather extremes.

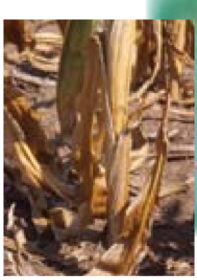
More rainfall concentrated into heavy downpours also increases the likelihood of water deficiencies at other times because of reductions in rainfall frequency. Another impact of heavy downpours is that wet conditions at harvest time result in reduced quality of many crops. Storm events with heavy rainfall are often 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 particularly vulnerable to weather extremes[16].

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[17]. For many high value vegetable 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[18].

Drought frequency and severity are projected to increase in the future, particularly under higher emissions scenarios[19]. Increased drought will be occurring at a time when crop water requirements are also increasing due to rising temperatures. All crops are negatively affected by water deficits[20].



While technological improvements have resulted in a general increase in corn yields, extreme weather events have caused dramatic reductions in yields in particular years. Increased variation in yield is likely to occur as temperatures increase and rainfall becomes more variable during the growing season. Yields are not expected to continue their historical upward trend as temperatures rise above the optimum for vegetative and reproductive growth.



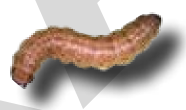
Weeds, diseases, and insect pests benefit from warming, and weeds also benefit from rising carbon dioxide, increasing stress on crop plants and requiring more pesticide and herbicide use.

Weeds benefit more than cash crops from higher temperatures and carbon dioxide (CO_2) levels[21]. One concern with continued warming is the northward expansion of invasive weeds. Southern farmers lose more to weeds than northern farmers. For example, southern farmers lose 64 percent of the soybean crop to weeds while northern farmers lose 22 percent[22]. 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 agricultural areas. Kudzu currently infests 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[23].

Increasing CO_2 reduces herbicide efficacy[45].

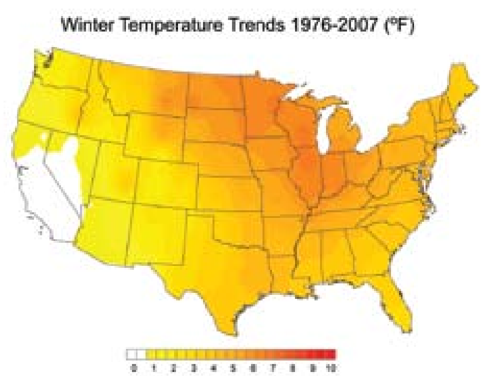
Controlling weeds currently costs the United States more than $11 billion a year, with the majority spent on herbicides[24]; so both herbicide use and costs will likely increase as temperatures and carbon dioxide levels rise. At the same time, the most widely used herbicide in the United States, glyphosate (RoundUp®), loses its efficacy on weeds grown at CO_2 levels that are projected to occur in the coming decades. Higher concentrations of the chemical and more frequent spraying will thus be needed, increasing economic and environmental costs associated with chemical use[25].

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 doing direct damage to 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[26]. 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 CO_2 conditions tend to be less nutritious, so insects have to eat more to meet their protein requirements, causing greater destruction to crops[27].



As a result of all of these factors, pesticide use will have to increase. Warmer areas already have to spray much more than cooler ones. For example, Florida sweet corn growers spray their fields 15 to 32 times a year to fight pests like corn borer and corn earworm, while New York farmers average only zero to five times. 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 the kinds of plants we'd least like to succeed is found in the response of poison ivy to rising CO_2 concentrations. Poison ivy thrives in air with extra CO_2 in it, growing bigger and producing a more toxic form of the oil, urushiol, that 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 CO_2 growth stimulation of poison ivy exceeds that of most other woody species. Given continued increases in CO_2 emissions, poison ivy is expected to become more abundant and more toxic in the future, with implications for forests and human health[28].

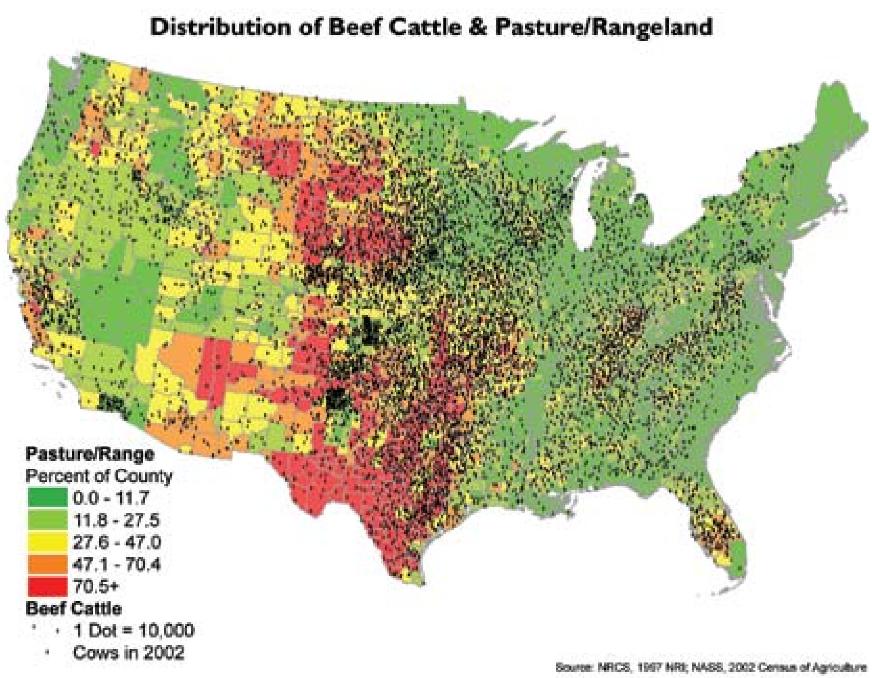


Winter temperatures are rising faster than in any other season, especially in many key agricultural regions. This allows many insect pests and crop diseases to expand and thrive, creating increasing challenges for agriculture. This map shows increases of over 7°F in winter temperatures in the Midwest and northern Great Plains over the past 30 years.

Forage quality in pasture and rangeland generally declines, reducing the land's ability to supply adequate livestock feed. Increased heat, disease, and weather extremes reduce livestock productivity.

Beef cattle production takes place in every state in the United States, with the greatest number raised in regions that have an abundance of native or planted pastures for grazing. Generally, eastern pasturelands are planted and managed, whereas western rangelands are native pastures, which are not seeded and which have much less rainfall. There are transformations now underway in many of these lands as a result of rising atmospheric carbon dioxide levels and the associated climate change, involving which species of grasses dominate, as well as quality changes within species. These changes are generally reducing the quality of the forage, so that more acreage is needed to provide animals with the same nutritional value, resulting in an overall decline in livestock productivity. In addition, woody shrubs and invasive cheatgrass are encroaching into grasslands, further reducing their forage value[30]. The combination of these factors leads to an overall decline in livestock productivity.

Rising atmospheric CO_2 levels impact forage quality because plant nitrogen and protein concentrations often decline with higher concentrations of CO_2[31]. This reduction in protein reduces forage quality and counters the positive effects of CO_2-enrichment on plant production and carbohydrates. Rising CO_2 may also reduce the digestibility of forages that are already of poor quality. Reductions in forage quality could have pronounced negative effects on animal growth, reproduction, and survival, and could render livestock production unsustainable unless animal diets are supplemented with protein, adding more costs to the production. On shortgrass steppe, for example, CO_2 enrichment reduced the protein concentration of autumn forage below critical maintenance levels for livestock in three out of four years and reduced the digestibility of forage by 14 percent in mid-season and by 10 percent in autumn. Significantly, the grass type that thrived the most under excess CO_2 conditions also had the lowest protein concentration[32].



At the scale of a region, the composition of forage plant species is determined mostly by climate and soils. The primary factor controlling the distribution and abundance of plants is water: both the amount of water plants use and water availability over time and space. The ability to predict 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, it has been observed that increasing CO_2 favors weeds and invasive plant species over native species because invasive species have traits (rapid growth rate, prolific seed production) that allow a larger growth response to CO_2. In addition, the effect of increasing CO_2 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[33].

Heat stress

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 U.S. climate warms, the more production will fall. For example, an analysis of warming in the range of 9 to 11ºF (as projected under higher emissions scenarios) projected a ten 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 2.7ºF caused less than a one 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[34].

Temperature and humidity interact to cause stress in animals, just as in humans.

Models project that increases in air temperatures in the central United States could create summer-time losses up to an estimated $93.3 million dollars per year by 2040 as a result of reductions in performance associated with lower feed intake and increased maintenance energy requirements. These losses do not account for the costs of increased death of livestock associated with extreme weather events such as heat waves. Costs of each event can exceed $25 million. 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 5000 head of cattle in a single heat wave in one summer[35].

Warming can also affect parasites and disease pathogens. The earlier arrival of spring and warmer winters allow greater proliferation and survival of parasites and disease pathogens. 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. In addition, changes in rainfall distributions could lead to changes in diseases sensitive to relative humidity.

Warming and rising carbon dioxide increase forest growth, but more insect outbreaks, fire, and drought have negative effects.

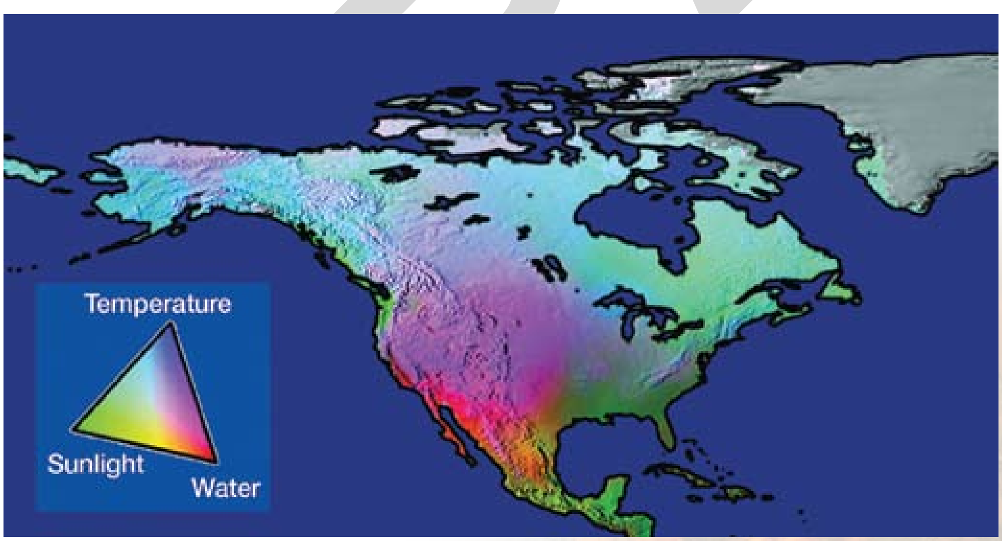
Forests cover about 740 million acres of the United States, about one-third of the nation. While occurring in every State, forests are most prevalent in the humid eastern United States, the West Coast, at higher elevations in the interior West and Southwest, and along river corridors in the plains states. Forests provide many services important to the wellbeing of Americans: water quality, water flow regulation and watershed protection; wildlife habitat and biodiversity conservation; recreational opportunities and aesthetic and spiritual fulfillment; raw materials for wood and paper products; climate regulation, carbon storage, and air quality. A changing climate will alter forests and the services they provide; most of these changes are likely to be detrimental.

In general, tree growth and productivity increase with rising temperatures and carbon dioxide levels if sufficient amounts of water and nutrients are available. Therefore, forest productivity is projected to increase in much of the East while decreasing in much of the West where water is scarce and projected to become more so. Wherever droughts increase, forest productivity will decrease and tree death will increase. In addition to occurring in much of the West, these conditions are projected to occur in Alaska and in the eastern part of the Southeast.

Distribution of forests in the continental United States by forest type[44].

Disturbances

Besides drought, other major forest disturbances include fires, insect outbreaks, and damage due to severe storms including hurricanes and ice storms. Disturbances are a necessary and natural part of forests, but they are now increasing as a result of human-induced climate change. Disturbances such as wildfire and insect outbreaks are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons.



Potential limits to vegetation productivity based on fundamental physiological limits by sunlight, water balance, and temperature. Nutrients are also important and vary locally[46].

Ponderosa pine forest after the Hayman fire in Colorado (US Forest Service Photo).

Fire

In the western United States, both the frequency of large wildfires and the length of the fire season have increased substantially in recent decades, due to earlier spring snowmelt and high spring and summer temperatures[36]. These changes in climate have reduced the availability of moisture, drying out the vegetation that provides the fuel for fires. Alaska has also experienced large increases in fire, with the area burned doubling in recent decades[37]. As in the western United States, air temperature is a key predictor of area burned with higher summer air temperatures causing an increase in area burned[38]. In Alaska, for example, June air temperatures alone explained approximately 38 percent of the increase in annual burned area during 1950 to 2003[39].

The increase in fires releases more carbon dioxide and soot, creating a feedback loop or cycle in which more warming causes more fires which result in more warming. In addition, increases in fires in Alaska and Canada have consequences for air quality in the central and eastern United States because winds often transport air pollution, including particulates and ground-level ozone, to the south.

Insects

Rising temperatures increase insect outbreaks in a number of ways. First, warmer winters allow larger populations of insects to survive the cold season that normally limits their numbers. Second, the longer warm season allows them to develop faster, sometimes completing two life cycles instead of one in a growing season. Third, warmer conditions help expand their ranges northward. And fourth, drought stress reduces trees ability to resist insect attack, for example, by pushing back against boring insects with the pressure of their sap. Spruce beetle, pine beetle, spruce budworm, and woolly adelgid (which attacks eastern hemlocks) are just some of the insects that are proliferating in the United States, causing devastation in many forests. These outbreaks are projected to increase with ongoing warming. Trees killed by insects also provide more dry fuel for wildfires.

Storms

Intense storms can cause enormous damage to forests creating feedbacks to climate. For example, Hurricane Katrina killed or caused severe structural damage to about 320 million large trees. As these trees decompose over the next few years, they will release an amount of carbon to the atmosphere equivalent to the total carbon taken up in a year by all U.S. forests[40].

Before and after Hurricane Katrina: satellite images of Gulf Coast forests show live trees in green and dead trees in red (Landsat 5 image, source: USGS).

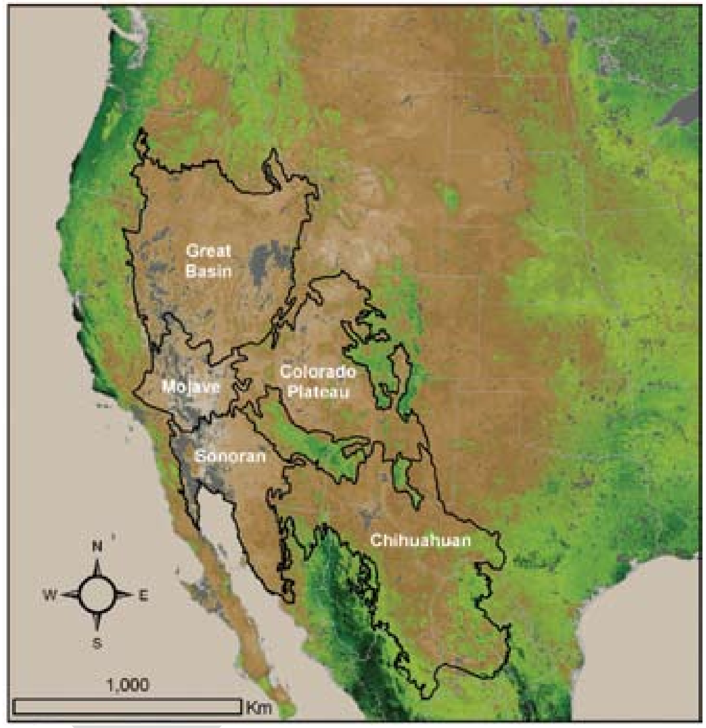
Deserts and dry lands become hotter and drier, creating a self-reinforcing cycle of invasive plants, fire, and erosion.

Forests and carbon storage

Forests in the United States currently offset about 20 percent of our nation's annual fossil fuel carbon emissions. This carbon "sink" is an enormous service provided by forests and its persistence or growth will be important to limiting atmospheric carbon dioxide concentrations. The scale of the challenge of increasing this sink is very large. To offset an additional 10 percent of the U.S. emissions through tree planting would require converting one-third of current croplands to forests [41].

Higher temperatures, increased drought, and more intense thunderstorms increase erosion and promote invasion by non-native grasses.

The arid region of the American Southwest is projected to become drier in this century. There is emerging evidence that suggests that these changes are already underway. Deserts in the United States are also projected to expand to the north, east and upward in elevation in response to projected warming and associated changes in climate.

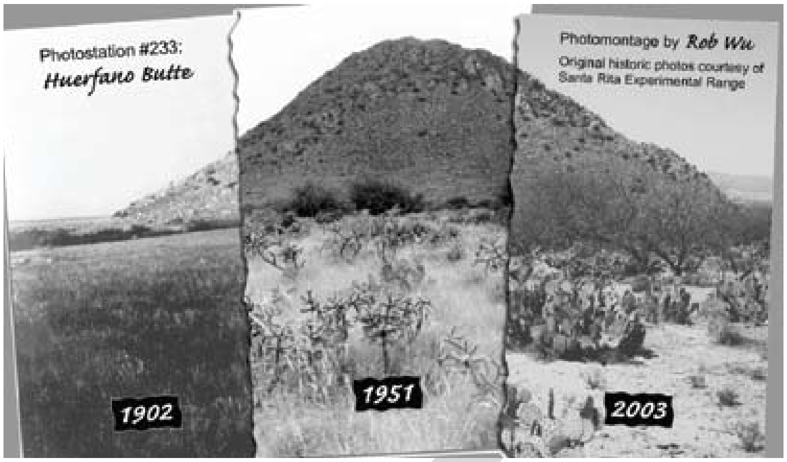


The five major North American deserts[I].

Increased drying in the region contributes to a variety of changes that exacerbate a cycle of desertification. Increased drought conditions cause perennial plants to die due to water stress and increased susceptibility to plant diseases. At the same time, non-native grasses have invaded the region. As these grasses increase in abundance, they provide more fuel for fires, causing fire frequency to increase in a self-reinforcing manner that leads to further losses of vegetation. When it does rain, the rain tends to come in heavy downpours, and since there is less vegetation to protect the soil, water erosion increases. Higher air temperatures and decreased soil moisture reduce soil stability, further exacerbating erosion. And with a growing population needing water for urban uses, hydroelectric generation, and agriculture, there is increasing pressure on mountain water sources that would otherwise flow to desert river areas[42].

The response of arid lands to climate change also depends on how other factors interact with climate at local scales. Large-scale, unregulated livestock grazing in the late 1800s and early 1900s in the Southwest is widely regarded as having contributed to widespread

desertification. Grazing peaked around 1920 on public lands in the West, and by the 1970s it had been reduced by about 70 percent. But arid lands are very slow to recover from the impacts of livestock grazing. Warmer and drier climate conditions are expected to further slow recovery. In addition, the land resource in the Southwest is currently managed more for providing water for people than for protecting the productivity of the landscape. As a result, the land resource is further degraded and recovery hampered[43].



Changes over the 100-year period are the result of grazing management and reduced rainfall in the region.

Adaptation Strategies for Agriculture

Change Planting Date: This can be an effective, no- or low-cost option for taking advantage of a longer growing season or avoiding crop exposure to adverse climatic conditions such as high temperature stress or low rainfall periods. Effectiveness will depend on the region and the rate and amount of warming. It is unlikely to be effective if the farmer goes to market when the supply/demand balance drives prices down. Predicting the optimum planting date for maximum profits will be very challenging in a future with increased uncertainty regarding climate effects on not only local productivity, but also on supply from competing regions.

Change Crop Varieties: Varieties with improved tolerance to heat or drought, or adapted to take advantage of a longer growing season, will be available for some crops. This is less likely to be cost-effective for perennial crops, where changing varieties is extremely expensive and new plantings take several years to reach maximum productivity. Even for annual crops, changing varieties is not always a low-cost option. Seed for new stress-tolerant varieties can be expensive, and new varieties often require investments in new planting equipment, or require adjustments in a wide range of farming practices. In some cases, genetic tolerance to elevated temperature may be difficult to breed for, and it may not be possible to identify an alternative variety that is adapted to the new climate and to local soils and practices, and also meets local market demands.

Change Crop or Livestock Species: This is a much more extreme, high-risk, and in most cases, high-cost option than changing crop varieties. While it could bring new and even increased profits in the long term, it requires the capital to essentially enter into a new business. Accurate predictions of climate trends, and development of the infrastructure and market for the new crops or livestock products would be essential to making this an effective response.

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

Changes in Water, Fertilizer, Herbicide, and Pesticide Use: Higher temperatures, longer growing seasons, and increased drought will lead to increased agricultural water use in some areas. Obtaining the maximum "carbon dioxide fertilization" benefit often requires more efficient use of water and fertilizers that better synchronizes 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.