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CHAPTER 22

Climate Change and Agriculture

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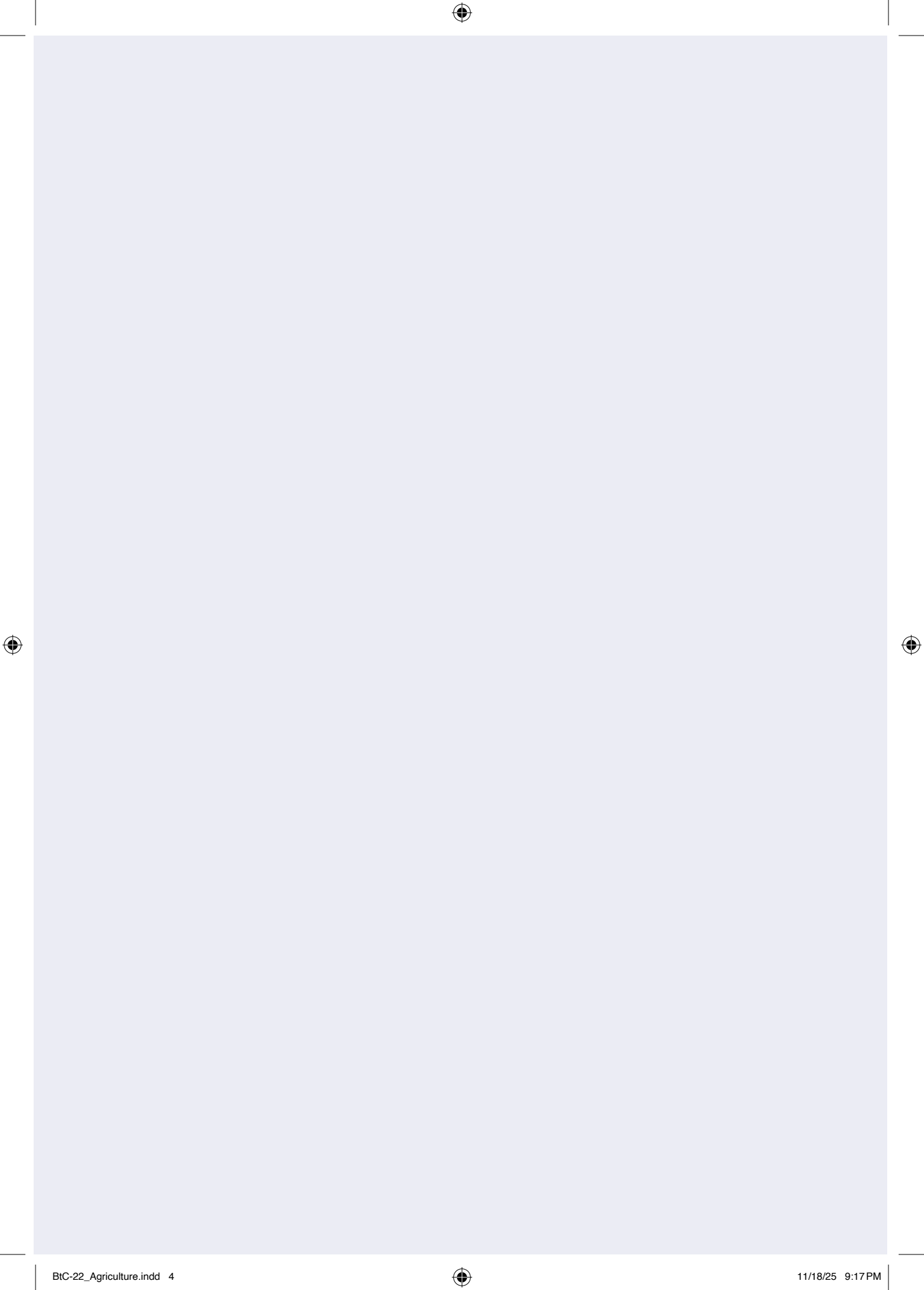


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Learning Objectives

1. Understand the interactions between climate change and agriculture.
2. Describe the impacts of climate change and agricultural practices on dust.
3. Connect climate impacts on agriculture to health impacts for society.
4. Identify potential solutions to the issues of climate change and agriculture.

Overview

Climate change is impacting agriculture through a range of direct and indirect effects. The feedback between climate and agriculture can be a closed loop or it can spiral out of control. Climate change is shifting rainfall patterns across the globe, leading to drought in some areas and excess rainfall and storms in others, where both extremes stress crops and agricultural animals. In addition, warming is shifting where crops can grow, increasing pest pressure, and limiting pollination success, while extreme heat is making some rangeland unusable. Elevated **carbon dioxide (CO₂)** may shift which crops are more successful, and it may make crops less nutritious. Overall, these climate shifts, along with intensive farm practices, may reduce soil health and sustainability.

Agriculture also has a large impact on climate change. Cattle and flooded rice farming are major sources of atmospheric **methane (CH₄)**, the second most important greenhouse gas (GHG). Overall, cattle generate up to 40%, and rice up to 11%, of global methane emissions. In addition, plant roots, trucking, and heavy machinery, as well as the generation of inorganic fertilizers, add a significant amount of CO₂ to the atmosphere, while excess fertilizer produces large amounts of **nitrous oxide (N₂O)**, a potent greenhouse gas. In addition, intensive agriculture and drought can lead to large amounts of dust and associated loss of topsoil.

However, we are on the verge of several innovations that may help to solve these challenges. The application of sensors and precise monitoring or “smart agriculture” can allow us to better conserve water and nutrients while maximizing crop growth. Crop breeding and novel molecular technology can help us to develop crops that are resistant to the challenges that climate change will pose. Intervening in the microbial communities in the cow rumen and rice **rhizosphere** can allow for reduction in methane emissions. Policy changes may allow and encourage us to adopt modern agricultural technologies and adapt to climatic shifts. Into the future, our informed societal choices can sustain food security as the climate changes.

22.1 Climate Impacts on Agriculture

As the climate changes, scientists have seen a range of impacts on agriculture, both direct and indirect, and they predict that impacts will continue. Overall, these impacts include weather changes that have led to drought, increased heat, longer growing seasons, and extreme weather events and flooding, as well as the direct effects of elevated CO₂ on crops.

Overall, global warming is positively correlated with extreme rainfall, because warmer air holds more moisture. For every degree that the temperature rises, the air can hold 6%–7% more water, which ultimately leads to heavier rainfall. At the same time, dry areas that experience less rainfall can be exacerbated by increased evaporation at higher temperatures. Tabari showed that in areas with high rainfall projected in climate models, there is a high likelihood of flood and extreme precipitation changes in seasonal water availability. Further, in drier regions, more extreme rain events on drier soils prevent absorption, causing the rainfall to be lost to runoff and evaporation. Many places where agriculture had been productive are now not receiving the necessary rainfall to support water-intensive crops, which will be exacerbated under future scenarios.

When rainfall and surface water access is limited due to shifting rainfall regimes, many farmers turn to the pumping of groundwater. This pumping is occurring at accelerating levels, leading to depletion of reserves, land subsidence, and shrinking options for the future. For example, Ouyang and colleagues showed that the Mississippi Embayment has faced significant groundwater depletion, exacerbated by complex climate change impacts, which indicates that groundwater pumping is causing the water table to drop rapidly over time. They saw that fluctuations in the water table were less prominent in forested areas than in cropland, highlighting the impact of land use on groundwater dynamics.

Climate change will bring a range of impacts on crop plant growth in particular. Kukal and Irmak used the existing variability in annual air

temperature changes since 1900 to determine the impact of warmer years on crop productivity. They found that overall growing seasons have increased in length, with an average increase of 12.7 days since the start of the twentieth century. This has generally benefited crop yield in most staple crops, including maize, soybeans, and spring wheat. These shifts in temperature have seemed to be advantageous for crop production, though some crops have shown other responses. However, the same longer growing seasons that can benefit crop growth throughout the year also allow pests to shift their distributions, expand their ranges, and increase their chances of surviving the winter, often expanding populations. These factors can lead to larger pest populations at the start of the growing season, rather than a building pest pressure throughout the growing season. For some organisms, this can also lead to much greater pest population sizes, such as for the European corn borer, which could respond to longer growing seasons by having additional generations per year, leading to more infestations and severe crop loss. Skendžić and colleagues stated that global climate warming could cause an increased risk of invasive insect species and insect-transmitted plant diseases.

Not all insects that interact with crops are pests. In fact, climate-change-induced shifts in growing season timing and duration, and range changes, may have important impacts on pollinators, as well as on the plants that require pollination. Trunschke and colleagues demonstrated that climate change will impact flower timing and abundances, and plant community composition. Across agricultural and natural systems, these changes will have consequences for pollinator visitation, pollination network structure, pollen transfer dynamics, and seed and crop production.

The issue of agricultural pests goes beyond plant diseases, as livestock production systems have been working to raise animals and protect them against disease for generations. A recent study by Frizzo and colleagues has shown that in intensive animal production, excessive use of antimicrobial substances paired with reduction in maternal contact and increased stress has led to digestive disorders from an imbalance in the intestinal microflora, which leads to a reduction in the natural resistance against contamination or pathogen colonization.

Climate-change-induced warming and drying across the US will

likely reduce soil water availability, net primary productivity, and other ecosystem processes in the southern Great Plains, the Southwest, and northern Mexico, decreasing rangeland. Boone and colleagues project that globally, cattle will decline 7.5% to 9.6%, an economic loss of from \$9.7 to \$12.6 billion by 2050. Livestock can be killed by extreme heat waves, and their water reserves may also become more toxic because, as Huang and colleagues observed, warming temperatures and heat waves increase phytoplankton blooms in reservoirs, which are often used for livestock watering. Many such blooms lead to high concentrations of cyanotoxins in water, which can poison livestock.

Elevated CO₂ will have a range of impacts on agricultural crops. When some crops are grown in higher concentrations of CO₂, their rate of photosynthesis increases, which then increases plant biomass, but it also leads to a decrease in nutritional content. Overall, the C3 plants, which include soybeans, wheat, and rice, benefit more from higher CO₂ concentrations, due to their limitations in carbon fixation, than do C4 plants, which include corn, sugarcane, and biofuels crops. C4 plants are already highly efficient at capturing CO₂, so they see a less pronounced response to increased CO₂ levels. While most C3 crops show lowered nutrient quality of seeds or grains under elevated CO₂, some C4 crops show great resilience to climate change. Bhargava and Mitra showed that sorghum, a C4 crop, is a “climate-change ready” crop, efficient at nutrient and water acquisition in a warmer world with elevated CO₂. Research over the past few decades shows that higher CO₂ concentrations could have a significant impact on ecosystems and soils, mainly by altering how plants process carbon. Since most soil organisms rely on carbon from plants, changes in plant photosynthesis due to higher CO₂ can greatly influence soil microbes, especially those near plant roots. The main effects are seen in plant metabolism and root secretions, particularly in C3 plants, which directly impact nearby microbial communities, including bacteria, fungi, and mycorrhizae.

While predicted climate changes include drought for many regions of the world, conversely heavy precipitation and extreme levels of storm surge are already being experienced in some coastal areas. Yangchen and colleagues reported that extreme flood days have increased by 1 to 4 days per decade on the East Coast of the US. Motha in 2011 showed

that most areas of the US have been experiencing severe moisture surplus since 1970, which has generated strong river pulses of nitrates and other nutrients. Such runoff with high nutrient levels may have contributed to the doubling in size of the Mississippi Gulf's "dead zone" in 1993. Most crops are sensitive to direct effects of flooding and other weather impacts during critical growth phases. Other effects on crops are indirect, through influences on soil processes, nutrient dynamics, and pest organisms.

One way to understand the ability of soil to grow nutritious plants is to evaluate the "soil health," which encompasses several important soil properties. The factors include bulk density, **water holding capacity** (ability to absorb water), soil aggregate stability, and **microbial diversity** (number of groups of different microorganisms in a sample), among others. Many agricultural systems around the world are declining due to issues like soil erosion, low productivity, and poor water quality, often caused by unsustainable farming practices. This decline decreases diversity and soil health. Declines in soil health lead to reductions in soil functions vital to agriculture, such as biomass production and soil carbon storage.

22.2 Agricultural Impacts on Climate

In addition to the range of impacts climate has on agriculture, there are many feedbacks from agriculture back to the climate. In particular, many aspects of agricultural production generate greenhouse gases in excess of natural production. Overall, CO_2 is produced by plant roots and plant-associated microorganisms and other organisms in the soil, whether associated with ecosystems or agricultural systems. There are also several other mechanisms by which agricultural systems emit CO_2 , CH_4 , and N_2O , the three most abundant greenhouse gases in the atmosphere. While CO_2 is the most abundant GHG in the atmosphere, each CH_4 molecule holds 28 times more heat in the atmosphere, and each molecule of N_2O holds 300 times more heat. Therefore, even though N_2O and CH_4 are far less abundant in the atmosphere, the agricultural impact on both of these gases is very important in our efforts to address climate change.

Cattle production of CH_4 is one of the main agricultural forms of GHG production. Tapio and colleagues showed that rumen microbial community composition impacts the methane produced by the cow. A review by McAllister and colleagues covers the contributing factors to the production of methane by ruminants and how changing those factors affects methane emissions. They conclude that promoting a shift in fermentation toward the production of propionate reduces methanogenesis, but methane production cannot be completely eliminated without harming the animal. Strategies for reducing methane emissions must consider that electron transfer between methanogens and other organisms in the rumen is crucial for fermentation efficiency.

Rice paddies (Figure 22.2.1) have emerged as the second major source of methane from agriculture. In comparisons of rice paddies and natural wetland soil, Were and colleagues found significantly higher CO_2 from rice paddy conditions than from natural conditions, and lower CH_4 from rice paddy than from natural conditions, but they determined



FIGURE 22.2.1 Rice paddy in Yuanyang, China. Photograph by Yulin Jia.

that fluxes of gas emissions are mainly influenced by water level. From net emissions of CH_4 and CO_2 , they conclude that rice paddy wetlands are overall contributors to total carbon emission. Continuing research toward understanding microbial processes that control methane production and consumption, with rice agriculture compared with natural ecosystems, may generate farming practices that reduce emissions.

Agriculture and fossil fuel use have significantly increased nitrogen emissions across the US, leading to excess nitrogen deposition in natural ecosystems. Efforts to reduce the emissions of nitrogen oxides have successfully decreased nitrate deposition, but ammonium deposition has actually risen in many areas. Unfortunately, levels of ammonia were not historically measured, due to lack of regulations, but recent data show that ammonia may account for 65% of total nitrogen deposition. Reducing overall nitrogen deposition will become more challenging without cutting ammonia emissions. Stevens and colleagues showed that the flux of N_2O from soil can be due to nitrification or denitrification. Since

aerobic and anaerobic microsites can develop within the same soil aggregate, excess nitrogen inputs into the soil can generate nitrogen gas emissions from a range of soil nitrogen cycling processes.

Overall, the greenhouse gas impacts from agriculture include emissions from food production, heavy machinery on the farm, food transportation, consumption, and waste processing, and go beyond the specifics covered in this text. For example, the Haber-Bosch process generates high levels of CO₂ emissions to break chemical bonds to generate ammonium, which is made into inorganic fertilizers. Generally, methane (natural gas) is burned to generate the energy to split water molecules, but Smith and colleagues have proposed using renewable energy to make this process cleaner.

22.3 Dust Is Driven by, and Impacts, Climate Change

One of the major impacts of intensive farming and climate-change-induced drought is the potential for soil loss and dust generation. With intensive farming and deep, frequent tillage, the aggregates and the associated soil structure that keeps the topsoil in place, and retains water, will break down. In addition, intensive cattle grazing will cause compaction of the soil, also disrupting this structure. Overall, this decreases the soil health, and associated water holding capacity, such that drought conditions are more severe for the soil, crops, and forage. When moisture is low, wind erosion generates dust while causing land degradation. This dust generation can reduce food production via substantially diminished yields of crops, pastures, and livestock.

In addition to the loss of topsoil and nutrients when soil is lost to dust generation, sand and dust storms have a negative impact on the agricultural sector when dust lands on crops. This can reduce crop yields by burying seedlings under sand deposits, causing the loss of plant tissue, and reducing photosynthetic activity. In addition, these storms can delay plant development, increasing drought impacts and killing livestock. Further, these storms can choke irrigation canals with sediment and reduce the water quality of rivers.

For the farmworkers who are exposed to dust generation on the farm, as well as sand and dust storms, exposure to fine particulate matter can increase health risks. Dust is routinely generated on high-intensity farms. In addition to generation of dust from soils, animal waste on the farm can dry out and generate harmful dust as well. From all of these sources, smaller dust particulates can get deep into lungs and cause respiratory illness. If the dust carries pathogenic bacteria or fungi, it can lead to infection. As climate change leads to more dust emissions, there are growing public health concerns about its effects on health.

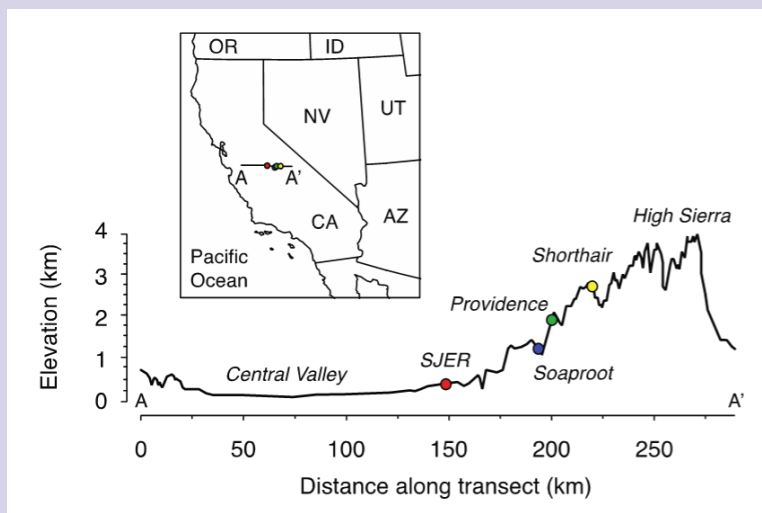
However, it is also clear that dust generated from topsoil can play

important roles in major biogeochemical cycles—especially the cycles of phosphorus, nitrogen, and iron. There are major implications of these cycles for the valuable environmental services provided by numerous ecosystems, both terrestrial and marine. These nutrients, which are among the macronutrients needed for all life, have particular significance for the formation of soil, as well as for the productivity of ecosystems and food webs in terrestrial and aquatic systems and for soil productivity in agricultural systems. The importance of mineral dust may be greatest in the oceans, as was demonstrated by Behrenfeld and colleagues. They performed a series of Ironex experiments, where they dumped mineral iron, as a proxy for terrestrial mineral dust, into oceans that had very low observed productivity. The photosynthetic microbial community responded with an enormous boost in photosynthesis, as measured in the increase in chlorophyll content of the surface waters, indicating that these communities are iron limited. This simulates a phenomenon that scientists believe has occurred in the past cycles of ice ages and thaws: when the Earth gets the warmest, there is enormous drought-induced dust generation; the more dust there is entering the oceans, the greater is the productivity of the oceans, and the greater is the removal of CO₂ from the atmosphere. The scientists believe that as CO₂ is removed from the atmosphere, the Earth starts to cool, the drought subsides, and the cycle begins to move toward the next ice age. While scientists do not want to bring on an ice age, numerous experiments have been conducted in recent years to determine whether dust can be used to reduce the harmful effects of climate change.

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Box 22.2.1

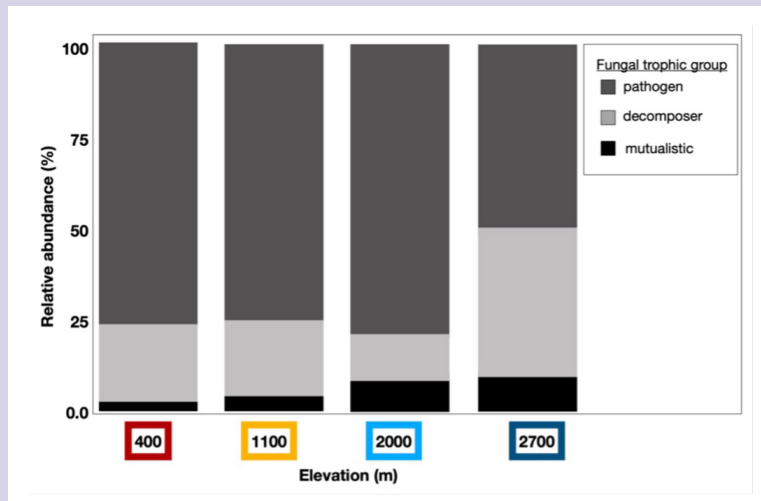
Drought Impacts on Dust in the Central Valley of California



Map (inset) showing distribution of study sites along an elevation transect through the Sierra Nevada, California. Sites span a 2.3-kilometer range in elevation and differ in distance from regional Central Valley dust sources by as much as 70 kilometers. Reproduced with permission from Aciego et al. 2017.

Dust provides ecosystem-sustaining nutrients to landscapes such as mountain ranges where many newly produced soils are lost to downhill erosion. All rocks and soils on Earth have an overall balance of rare elements and isotopes, which can allow scientists to trace the origin of material around the globe. Using the rare isotopes of the elements strontium and neodymium, Aciego and colleagues showed that Asian sources contributed up to 45% of dust deposition across an elevation gradient in the Sierra Nevada, California (top figure). The remaining dust originates regionally from the nearby Central Valley, which was experiencing extreme drought and massive dust storms when the study was performed, in 2014–2015. From both source locations, dust phosphorus entering the Sierra Nevada may be the most important source of phosphorus for the trees of these forests, including the giant sequoia. In addition, the microbial community in the dust showed variation with elevation, with more fungal

pathogens in dust coming from the Central Valley, which was greater entering the lower elevations (bottom figure).



Relative abundance of pathogenic versus decomposer and mutualist fungi in dust entering the Sierra Nevada at four elevations. Reproduced with permission from Maltz et al. 2022.

22.4 Solutions to Climate and Agriculture Issues

While the issues related to climate and agriculture are complex, there are many possible solutions to these problems under development. Generally, these solutions address ways to make agriculture more resilient to the shifts projected in the climate. Crop breeding, including the use of novel technologies, can increase the drought and disease resistance of plants, along with their physical stability in the face of storms. At the same time, a range of innovations can change or limit the microbial communities involved in methane production across agricultural systems. Finally, there are several policy solutions that can address these issues on a macro scale, in particular incentivizing certain crops in the newly beneficial locations, and mandating climate-smart farming practices.

There is a movement toward “climate-smart” solutions in agriculture, which rely on arrays of sensors in the soils and the plants, paired with digital agricultural decision support systems. These approaches can improve society’s disaster preparedness and optimize our ability to provide humanitarian aid as needed. Etherton and colleagues have suggested actions for improving food security before and following disasters. These actions include (1) strengthened regional and global cooperation, (2) capacity building for new technologies, (3) protected seed systems to replace seed lost in disasters, (4) buildup of biosecurity infrastructure and risk assessment tools, and (5) decision support systems that can adapt to unexpected scenarios. In 2023 Karunathilake and colleagues laid out a range of recent precision agriculture innovations—like the solar-powered sampler shown in Figure 22.4.1, drones, and machine learning computations—as well as the limitations imposed by these new approaches, such as data management, technology adaptation, and cost-effectiveness.

As we look to future solutions, we recall that healthy soils are crucial for agricultural success. When farms use organic instead of inorganic

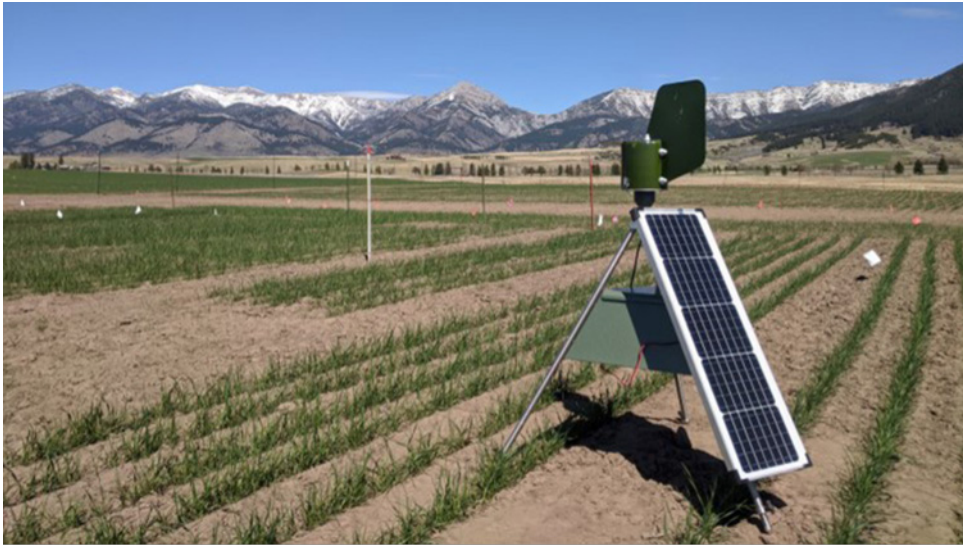


FIGURE 22.4.1 Solar-powered cyclone spore sampler, used to capture airborne pathogen spores in winter fields. Photograph from Uta McKelvy.

fertilizer, there are far-ranging effects including increases in plant growth, crop quality, and soil health, which are vital for food security into the future. In addition, waste management methods like composting and anaerobic digestion for farm animal waste generate useful organic fertilizers. Precise calculations allow for optimal fertilizer use to enhance beneficial soil microorganisms and protect crops from diseases, allowing farming to be sustainable. Lal showed that restoration of degraded soils with a set of beneficial soil management techniques, along with conversion of degraded agricultural areas to rangeland and forest, will allow carbon sequestration and increase sustainable agricultural productivity. Mulch farming, establishing cover crops, and precision agriculture with integrated nutrient management will aid in soil health restoration of degraded land in the future.

Crop breeding for resilience and future climates would include drought-resistant crops and those that are able to withstand both pests and the diseases associated with flooding, such as mold and mildews. In addition, crop breeding for physical stability would allow agricultural plants to withstand the physical assault of more intense storms. The use of traditional crop breeding techniques can be augmented through

the use of the clustered regularly interspaced short palindromic repeats (CRISPR) genome-editing technology. CRISPR genome-editing technology opens new opportunities to engineer disease resistance traits. These traits can include resistance to viruses, bacteria, fungi, and pests as well as the physical stresses of climate change. The challenges posed by climate demonstrate an urgent need for updated pest management strategies, including the use of predictive modeling tools, to work hand in hand with crop breeding techniques. The CRISPR/Cas 9 system has been used successfully to edit rice genes for stress tolerance and resistance.

In addition to the mechanisms above aimed toward keeping agriculture sustainable into the future, a range of approaches is being developed to reduce agricultural GHG production. In general, a movement away from bovine production systems and overall consumption can assist with decreasing methane production. One approach involves the modification of cattle rumen microbiomes, where a lot of progress has been made. Aristimuño Ficooseco and colleagues emphasize the effects of probiotic bacteria, including *Lactobacillus acidophilus*, *Limosilactobacillus fermentum*, and *Limosilactobacillus mucosae*, as feed probiotics, which may reduce methane emissions and improve cattle milk production. Beyond microbiome adjustment directly, a wide range of feed additives can decrease methane emissions from cattle.

While microbial methane production occurs throughout the flooded soil of rice paddies, methane oxidation in rice fields is localized in the rhizosphere of the rice plants, because oxygen is leaked out of the roots. Possible mitigation for methane emissions could involve the exploitation of the variety of morphological and physiological properties of rice to select cultivars that maximize CH₄ consumption in the rhizosphere. Kwon and colleagues argue that through water and fertilizer management, breeding of new rice cultivars, regulating root exudation, and manipulating rhizosphere microbiota, rice agriculture can be limited in its impact on GHG production in the near future.

There are also ways to potentially reduce GHG production from the entire agricultural system. With use of renewable energy to charge battery-based electric machinery and trucks, enormous parts of the agricultural system can be made carbon-neutral. Bicer and colleagues

also showed that the environmental impacts of inorganic fertilizer production can be reduced by using nuclear electrolysis-based ammonia generation methods. This would yield the lowest global warming and climate change impacts, while generating the fertilizer used in many modern production systems.

Sources for the Figures

Figure 22.2.1. Photograph by Yulin Jia (US Department of Agriculture: Dale Bumpers National Rice Research Center), CC BY 2.0. <https://creativecommons.org/licenses/by/2.0>, via Wikimedia Commons.

Box 22.2.1 top figure: Aciego, S. M., et al. 2017. Dust outpaces bedrock in nutrient supply to montane forest ecosystems. *Nature Communications* 8(1), 14800.

Box 22.2.1 bottom figure: Maltz, M. R., et al. 2022. Landscape topography and regional drought alters dust microbiomes in the Sierra Nevada of California. *Frontiers in Microbiology* 13, 856454.

Figure 22.4.1. Photograph from Uta McKelvy, Mary Burrows (MSU). Graduate student: Karl Everet Owen. <https://www.montana.edu/extension/plantpath/research/index.html>.

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Chapter Glossary

Following is a list of terms and acronyms used in the chapter.

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online glossary

TABLE 22.4.1 Glossary Items

Term	Definition
N ₂ O	Nitrous oxide
CO ₂	Carbon dioxide
CH ₄	Methane
water holding capacity	The ability of soil to absorb water
microbial diversity	The number of groups of different microorganisms in a sample
rhizosphere	The zone of influence of the roots of a plant