SOAR

STATE-OF-THE-ART REPORT (SOAR)
JULY 2023

HDIAC-BCO-2022-425

AGRICULTURAL SECURITY: IMPACTS ON MILITARY READINESS AND NATIONAL SECURITY

By Deanna C. Milonas and Steven B. Freudenberger
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DEANNA C. MILONAS AND STEVEN B. FREUDENBERGER

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ABSTRACT

The food and agriculture (FA) sector is designated as one of the 16 critical infrastructures that contribute to U.S. economic stability and security. Vulnerabilities in the FA sector pose a threat to food security, national security, and military readiness. Food insecurity and hunger are a cost of war and often lead to the viscous cycle of further protest and violent conflict. This state-of-the-art report examines the impacts that climate change, threats of bioterrorism, and cyberattacks pose on food security and explores the technologies, techniques, and policies to mitigate those vulnerabilities.

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EXECUTIVE SUMMARY

This state-of-the-art report examines the current state and future challenges of the U.S. food and agriculture (FA) sector, which is one of the 16 critical infrastructures and a significant contributor to the U.S. economy. The FA sector encompasses a complex and interdependent system of production, processing, distribution, and consumption of food and agricultural products. The FA sector provides food security, nutrition, health, income, and employment to the United States and the world's population. This report also identifies the problem of food insecurity in U.S. households and active military personnel, which could impact the nations Warfighter health, well-being, and performance.

This report identifies three main threats to the FA sector: (1) climate change, (2) agroterrorism, and (3) cyberattacks. These threats can affect various aspects of the FA sector such as food production; international trade; market stability; quality of agriculture products; and, ultimately, the price and affordability of the nation's food. These impacts could eventually impact national security.

1. Climate change is the long-term alteration of weather patterns and environmental conditions due to human activities such as greenhouse gas emissions. It can affect crop yields, quality, livestock health, productivity, irrigation water demand, soil erosion, pest and disease outbreaks, and food prices and affordability. For example, climate change could cause more frequent and intense droughts in some regions such as the U.S. Southwest. This could reduce crop production and irrigation water availability, increase water stress for crops and livestock, increase soil salinization and degradation, increase wildfire risk, reduce hydropower generation, increase energy demand for cooling, increase migration and displacement of populations, and increase conflict over water resources.
2. Agroterrorism is the deliberate introduction of a disease agent or toxin into crops or livestock with the intent to cause harm or fear. Agroterrorism can affect the FA sector by causing widespread losses or contamination of crops or livestock, disrupting trade or markets, creating public health or animal health emergencies, eroding consumer confidence, and imposing significant costs for response and recovery. Agroterrorism can also have spillover effects on other sectors such as tourism, transportation, energy, and environment and threaten national security and the military's readiness.
3. Cyberattacks are malicious actions that target the information systems, networks, devices, and infrastructure that support food production, processing, distribution, and consumption. Cyberattacks can compromise the data integrity, confidentiality, and availability of the FA sector, cause physical damage, disrupt operations, cause financial losses, harm reputation, endanger safety, and undermine security. Cyberattacks can target various components of the FA sector such as sensors, unmanned systems, software, internet platforms, databases, control systems, and communication systems.

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SECTION 01 INTRODUCTION

1.1 OVERVIEW

An army marches on its stomach [1]. This adage, attributed both to Napoleon Bonaparte and Frederick the Great, is as true today as it was in the 19th century. The differences today are that the climate is rapidly changing and technology is playing a much greater role in producing food. The changing climate threatens the food supply, the advancing technology leaves gaps for adversaries to exploit, and that same technology must be secured to protect the nation's access to the food supply. Additionally, the military's food supply depends on the nation's food supply, and any disruption to the nation's food supply could impact the military's readiness.

This report discusses the national security implications of the food and agriculture (FA) sector in the United States and the threats that could disrupt the production and distribution of food. It focuses on the threats of climate change, biological outbreaks, and cybersecurity. The important key to take away is that the vulnerabilities to the FA sector are a complex problem and cannot be viewed as individual threats.

In recent years, the FA sector has experienced an increase in the frequency and intensity of severe weather events due to climate change [2]. These events can cause direct damage to crops and livestock by exposing them to extreme temperatures, water stress, soil erosion, and fire. They can also indirectly affect agricultural productivity by altering the distribution and severity of pests and pathogens that can reduce crop yields and quality. Moreover, severe weather events can disrupt the infrastructure and supply chains that support the FA sector, such as transportation, storage, processing, and distribution systems. Climate change is a current and significant threat to the FA sector. The problem is complex because climate change threatens food security at the very foundation of food production, which is a significant threat to agricultural sustainability and can also cause more stress on the agriculture system and make it more vulnerable to the introduction of pathogens or biosecurity threats [3]. As agriculture production increases, it will lead to an increase in greenhouse gas (GHG) emissions, which only worsens the impacts of climate change, so it needs to be done in a way that minimizes the release of GHG emissions. However, the solution to solve this may exacerbate the issue.

The FA sector also faces potential threats from deliberate or accidental introduction of biological agents that can harm crops or animals. These agents include bacteria, viruses, fungi, insects, weeds, and toxins that can cause diseases or damage to agricultural products [4, 5]. Such threats are known as agroterrorism or bioterrorism and can be motivated by political, ideological, economic, or personal reasons. Agroterrorism or bioterrorism can have devastating impacts on the FA sector by reducing production, increasing costs, disrupting trade, and eroding consumer confidence [6]. They can also pose serious health risks to humans and animals that consume contaminated food or water [4, 5].

Another emerging threat to the FA sector is the possibility of cyberattacks that target the information and communication technologies (ICTs) that enable the operation and management of agricultural systems [7]. These ICTs include sensors, controllers, networks, databases, software applications, and cloud services that collect, store, process, and transmit data on various aspects of agricultural production [8]. Cyberattacks can compromise the confidentiality, integrity, or availability of these data and systems, resulting in loss of information, disruption of operations, damage to equipment, or theft of intellectual property (IP).

These threats can have serious implications for food security, economic stability, and national security. These incidents can result in loss of livelihoods for farmers, workers, and consumers and can also damage crops and livestock, affecting food production, processing, and distribution. This disruption can lead to food price increases and shortages that can exacerbate food insecurity for the consumer. Food insecurity can, in turn, contribute to instability at the local, national, and international levels and pose national security risks for the United States and the international community.

Compounding the threats, it is expected that, by 2050, the global population will reach 9.7 billion—1.9 billion more people than in 2020 [9]. It is estimated that it will require a 50% increase in agricultural production to feed the growing population and a 15% increase in water withdrawals by 2050 [9, 10]. As the population increases, the available agricultural land is also decreasing and being turned into urban areas. Doubling agriculture capacity by increasing farm acreage will not be an option because of limited availability of farmable land due to urban sprawl, climate change, and limited water access [11]. Increasing farming efficiency and decreasing food waste will need to improve to reach the food capacity to feed the world population by 2050.

This means that the agriculture sector will have to adopt more innovative and sustainable practices and technologies that can increase the productivity and quality of crops and livestock while reducing the environmental and social impacts. For example, some of these practices and technologies include precision agriculture, biotechnology advances, irrigation management, soil health improvement, integrated pest management, urban agriculture, and vertical farming. These practices and technologies can help optimize the use of land, water, energy, fertilizer, pesticides, and other inputs; enhance the resilience and diversity of crops and livestock; reduce GHG emissions and pollution; conserve natural resources and biodiversity; and improve food safety and nutrition. Decreasing food waste will require more efficient and equitable distribution and consumption of food along the supply chain from farm to fork. For example, strategies to reduce food waste include improving infrastructure and logistics, enhancing postharvest handling and storage, and promoting food processing and preservation. These strategies can help minimize food losses and spoilage and extend shelf life and availability of food. It is important now to address the challenges and opportunities of increasing agricultural production and decreasing food waste to ensure food security for present and future generations.

1.2 METHODOLOGY

This state-of-the-art report aims to analyze the current and future challenges for the agriculture sector in relation to climate change, agroterrorism, and cyberterrorism and determine how these threats impact the U.S. Department of Defense (DoD). The main sources of data are:

- Open-Source Internet Information: This report reviews relevant literature, reports, news articles, blogs, podcasts, videos, and social-media posts from credible and authoritative sources that provide insight into the topics of interest. It uses online tools such as Google Scholar, Web of Science, Institute of Electrical and Electronics Engineers (IEEE), Multidisciplinary Publishing Institute, ScienceDirect, PubMed, Scopus, and Proceedings of the National Academy of Sciences to search for academic publications and databases. This report focuses on sources that address the linkages and implications of climate change, agroterrorism, and cyberterrorism for the agriculture sector and the DoD.

- Government Sites: This report consults official websites of government agencies, departments, and organizations that are involved in or related to the agriculture sector, climate change, agroterrorism, and cyberterrorism. It uses websites such as Defense Technical Information Center, dtic.mil; U.S. Department of Agriculture (USDA), USDA.gov; U.S. Environmental Protection Agency (EPA), EPA.gov; U.S. Department of Homeland Security (DHS), DHS.gov; Federal Bureau of Investigation (FBI), FBI.gov; Central Intelligence Agency (CIA), CIA.gov; National Geospatial Intelligence Agency, NGA.mil; and the Homeland Security Digital Library, hsdl.org, to access data, statistics, reports, policies, strategies, plans, programs, initiatives, and best practices. This report pays special attention to websites that provide information on the DoD's role and responsibilities in protecting the agriculture sector and responding to climate change, agroterrorism, and cyberterrorism threats.
- Subject Matter Experts: This report uses interviews and surveys from experts in the fields of agriculture, cybersecurity, and biology who have knowledge and experience in dealing with climate change, agroterrorism, and cyberterrorism issues. Experts were selected based on their credentials, publications, affiliations, and recommendations.

1.3 U.S. AGRICULTURE OVERVIEW

The United States has 16 critical infrastructure sectors such as energy, transportation, and water. These sectors are so essential to U.S. security and public safety that any incapacitation or destruction would have a debilitating effect on national and economic security and public safety [12]. The FA sector is one of the 16 critical infrastructure sectors discussed in this report.

Agriculture is a significant part of the U.S. economy, with millions of people employed in the industry. In 2021, the output of America's farms contributed $164.7 billion or about 0.7% of U.S. gross domestic product (GDP). Agriculture not only directly contributes to the U.S. GDP but also indirectly contributes due to the sectors that rely on agricultural inputs. These sectors include "food and beverage manufacturing; food and beverage stores; food services; textiles, apparel, and leather products; and forestry and fishing." In 2021, agriculture's impact to the U.S. economy was $1.264 trillion to U.S. GDP—a 5.4% share shown in Figure 1-1 [13].

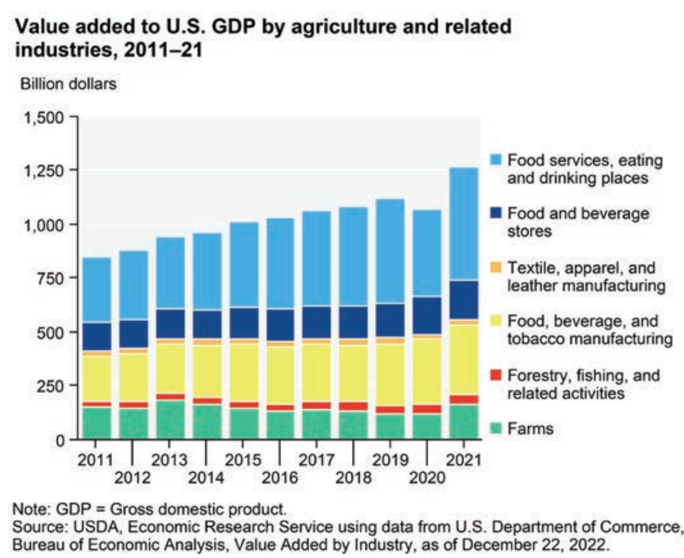

Figure 1-1. Value Added to U.S. GDP by Agriculture and Related Industries, 2011–2021 *(Source: Economic Research Service, U.S. Department of Agriculture [13]).*

In 2021, the FA sector created 21.1 million full- and part-time jobs, which is 10.5% of total U.S. employment. This means that one out of every eight Americans works in an occupation directly supported by food production. Direct, on-farm employment accounted for 2.6 million jobs, which is 1.3% of total U.S. employment, as shown in Figure 1-2 [13].

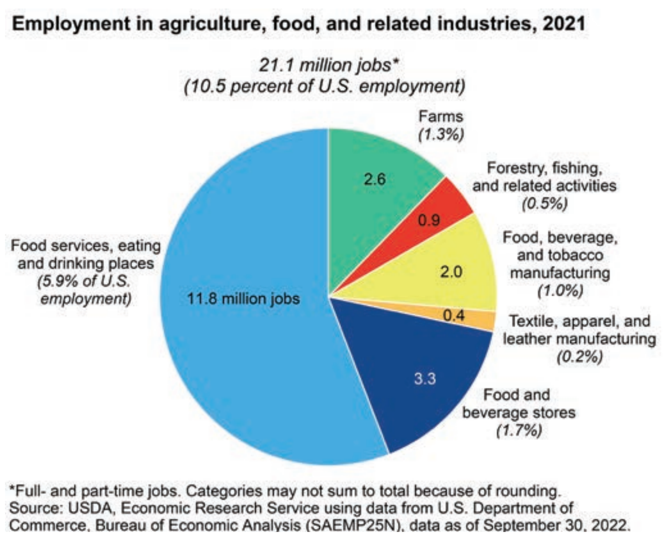

Figure 1-2. Employment in Agriculture, Food, and Related Industries, 2021 *(Source: Economic Research Service, U.S. Department of Agriculture [13])*.

The FA sector is diverse and includes both large, commercial farms and small, family-owned operations. In the early 20th century, agriculture was very labor intensive and took place on many small, diversified farms in rural areas. In the 21st century, agricultural operations shifted toward a smaller number of large, specialized farms. This is due to advances in agricultural technology and transportation, changes in government policy, and market demands [14].

This shift can be seen in Figure 1-3. The graph shows that from 1935 to the 1970s, the number of U.S. farms was rapidly declining while the average farm size was rapidly increasing [14]. This is the largest number of farms being consolidated or sold than in any other period in U.S. history. Meanwhile,

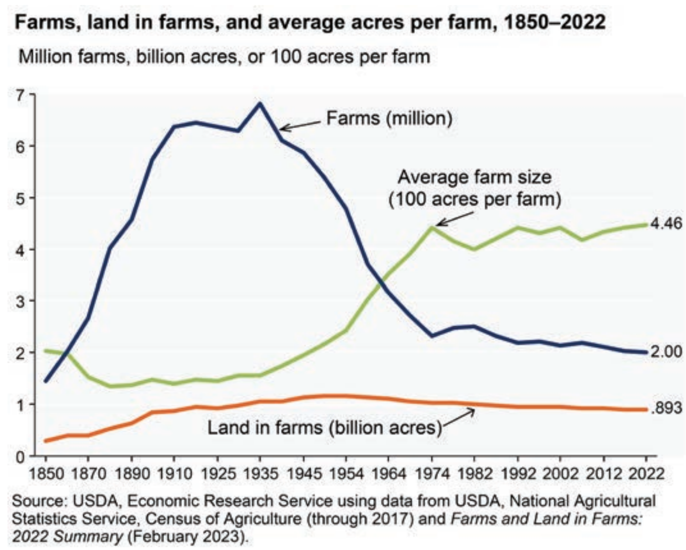

Figure 1-3. Farms, Lands in Farms, and Average Acers per Farm, 1850–2022 *(Source: Economic Research Service, U.S. Department of Agriculture [14])*.

the productivity of the farms continued to increase on roughly the same amount of farmland in the United States, which was due to the consolidated farms becoming more specialized [15]. From 1982–2022, the number of farms continued to decrease, but at a much slower rate. During that time period, farm size also increased, but only slightly [14]. As U.S. agriculture is trending toward a smaller number of large, specialized farms, they are becoming more vulnerable and any disruptions due to climate change, biological outbreak, or cyberattack could cause a greater impact to the U.S. food supply.

The U.S. crop industry is a crucial component of the country's economy and plays a significant role in the world's food supply. Just a handful of crops provide most U.S. food, with the world's food supply heavily dependent on a relatively small number of plant species. According to the International Development Research Center, the world's food supply depends on about 150 plant species, with just 12 providing three-quarters of the world's food [16]. Some of the most prevalent grown crops in the United States are corn, soybeans, hay, wheat, cotton, rice, sorghum, barley, oats, and peanuts. This can be seen in Figure 1-4, which shows a summary of the U.S. crop industry in 2021. Corn is the top-producing crop in terms of total production and acreage. Soybeans are the second-largest crop grown in the United States [17]. In 2018, the United States was the world's largest producer of corn and soy, accounting for 35% of the world's supply of each.

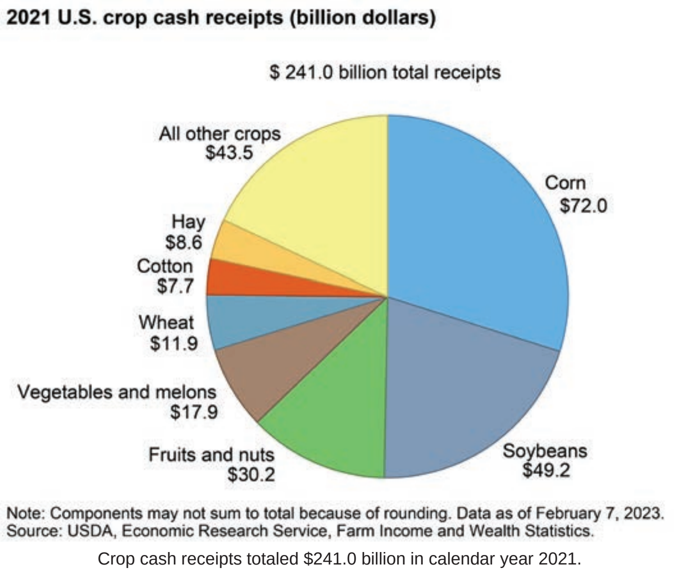

Figure 1-4. Summary of Crop Receipts *(Source: Economic Research Service, U.S. Department of Agriculture [14])*.

Although most agricultural products are used domestically, the United States is also a major exporter, with 50% soybeans, 21% corn, and 46% wheat [18]. Even though the United States is a major wheat exporter, it only grows about 6–7% of the world's wheat. It usually ranks in the top-three global wheat exporters, with Russia and the European Union surpassing it [19].

The U.S. livestock industry is a major component of the country's agriculture sector and a significant player in the global crop industry. In 2021, U.S. farm cash receipts from animal and animal products totaled $195.8 billion, with receipts for cattle and calves leading at $72.9 billion (37%) [20]. This can be seen in Figure 1-5, which shows a summary of the 2021 U.S. livestock industry. Currently, the

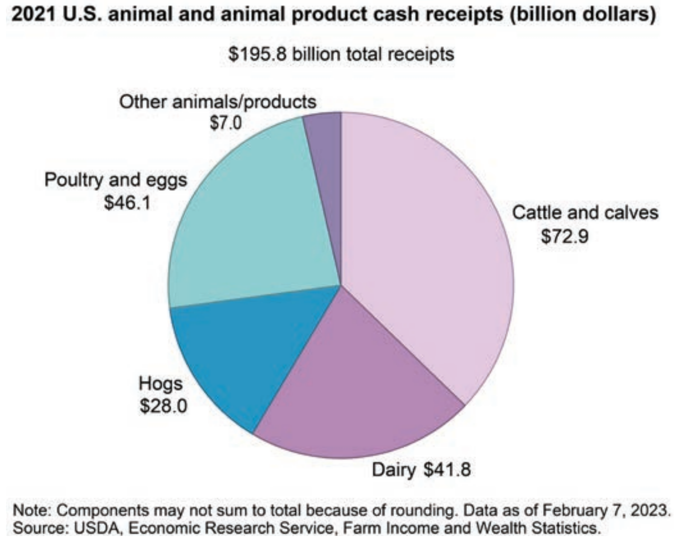

Figure 1-5. Summary of Livestock Receipts *(Source: Wessels Living History Farm [15])*.

United States is the world's largest producer and consumer of beef, producing more than 11.4 million metric tons every year [21]. In 2022, 15.2% of U.S. beef production was exported [22]. Japan and South Korea are two of the largest beef-export markets and accounted for about 47% of U.S. exports in 2021 [21]. The United States is also the second-largest cow milk producer in the world behind the European Union [23] and exports nearly 18% of its milk products [24]. The largest dairy markets are Mexico, China, and Canada [25]. The United States is the world's third-largest producer of pork behind China and the European Union and is one of the world's top exporters of pork and pork products. China, Japan, and Mexico are the top-three export markets for pork, accounting for 66% of exports [26]. The United States is the world's largest poultry producer and a major egg producer. It is the second-largest exporter of poultry meat, with almost 18% of total poultry production exported. The largest markets for U.S. poultry are Mexico, Hong Kong, and Canada [27].

Agricultural exports, or the share of U.S. agricultural and food production sold outside the country, indicate how much these sectors depend on foreign markets. They also show the demand for

U.S. agricultural products in international markets and how much U.S. farmers and food producers rely on foreign consumers for their sales and revenue. From 2010–2020, the United States exported an average of 23% of its agricultural products and 22% of its manufactured agriculture products [28]. In 2020, 87.3% of the food and beverages purchased by U.S. consumers was produced domestically, while the remaining 12.7% was imported [29]. In 2021, the American agricultural industry achieved its highest annual export levels ever recorded. The U.S. exported $177 billion of products, which was an 18% increase over the previous year and a 14.6% increase over the previous record set in 2014. Eight of the fifteen top U.S. export destinations increased their value of imports by record numbers. China was the top export destination, importing $33 billion worth of products, followed by Mexico at $25.5 billion and Canada at $25 billion. These were record figures for all three nations [30].

As discussed, the U.S. FA sector is a diverse and robust industry, providing food and raw materials for domestic consumption and export and a significant contributor to the country's economy. Despite the size and strength of the U.S. FA sector, millions of Americans still experience food insecurity every year. The U.S. FA sector is vulnerable to various challenges that can contribute to food insecurity, which is discussed in the next section.

1.4 U.S. FOOD INSECURITY OVERVIEW

According to the USDA, food insecurity is the "household-level economic and social condition of limited or uncertain access to adequate food" [31]. The USDA categorizes food security into four levels [32]:

1. High Food Security: "Households had no problems, or anxiety about, consistently accessing adequate food."
2. Marginal Food Security: "Households had problems at times, or anxiety about, accessing adequate food, but the quality, variety, and quantity of their food intake were not substantially reduced."
3. Low Food Security: "Households reduced the quality, variety, and desirability of their diets, but the quantity of food intake and normal eating patterns were not substantially disrupted."
4. Very Low Food Security: "At times during the year, eating patterns of one or more household members were disrupted and food intake reduced because the household lacked money and other resources for food."

Food insecurity is a problem in the United States. In 2021, 10.2% (13.5 million) of U.S. households experienced food insecurity at some point during the year, with a similar rate of 10.5% in 2020. Furthermore, 6.4% (8.4 million) of U.S. households had low food security in 2021 [33].

Food insecurity can affect the general population and can also affect active-duty military personnel. A 2019 survey by the USDA-Economic Research Service (ERS) and the U.S. Army Public Health Center at a major U.S. Army installation found that nearly 33% of over 5,600 respondents were marginally food insecure [34]. Moreover, a 2021 report by the USDA-ERS on food insecurity among working-age veterans showed that from 2015–2019, 11.1% of working-age veterans (between the ages of 18–64) "lived in food-insecure households, and 5.3% lived in households with very low food security, meaning the food intake of some household members is reduced and normal eating patterns disrupted due to limited resources" [35]. A 2023 study directed by the 2020 National Defense Authorization Act report confirmed the 2019 survey and revealed that active-duty food insecurity is a significant issue, with 24% of active-duty service members lacking consistent access to enough food for their households. In 2018, 15.4% of troops had low food security, and 10.4% had very low food security according to the U.S. Department of Agriculture criteria [36]. The causes of food insecurity in military families include lower salaries at lower ranks, high unemployment rates for military spouses, high cost of living near military bases, and ineligibility for food-assistance programs [36].

Food insecurity can also affect the military by compromising the U.S. food supply. The food subsistence program of the Defense Logistics Agency oversees providing food for the soldiers in the field and in the military's dining halls [37]. This program relies on local and regional resources and infrastructure, such as farmers and ranchers, processors, distributors, retailers, transporters, utilities, and regulators. Any disruption in these dependencies, caused by natural disasters, cyberattacks, or terrorist attacks, could threaten the military's readiness inside and outside the country. These disruptions can also occur at single dining facilities in forward operational environments. The risk of deliberate contamination of food that could harm the preparedness of the fighting force requires more attention to troop feeding operations. The consequences can be serious if a single dining facility in a forward operational environment is targeted [38, 39].

In 2020, U.S. households spent 11.9% of their expenditures on food, which is the third-highest expenditure behind housing (34.9%) and transportation (16%) seen in Figure 1-6 [13]. Inflation is therefore something that very much affects food security. Even with the record levels of U.S. agriculture products and U.S. exports, U.S. and world food prices have continued to escalate, causing a new 15-year high in people experiencing food insecurity around the world [40].

The COVID-19 pandemic revealed how a novel virus can affect food insecurity by disrupting food availability globally due to labor shortages, production challenges, and distribution problems. These disruptions led to higher prices, lower quality, and a reduced variety of food products. According to a 2022 report by the Food and

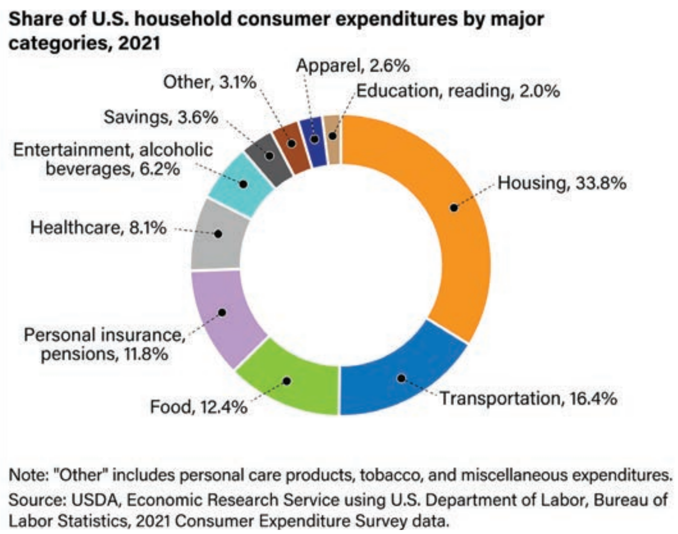

Figure 1-6. Share of U.S. Household Consumer Expenditures by Major Categories, 2021 *(Source: Economic Research Service, U.S. Department of Agriculture [13])*.

Agriculture Organization (FAO), around 2.3 billion people (29.3% of the world population) were moderately or severely food insecure in 2021, an increase of 350 million compared to before the pandemic. Nearly 924 million people (11.7%) faced severe food insecurity, an increase of 207 million [41].

1.5 SETTING THE STAGE

The U.S. agriculture sector is a critical and strategic component of the nation's economy, security, and public health. It provides food, fuel, and jobs for millions of Americans and contributes to the global food supply and trade. However, the U.S. agriculture sector also faces significant threats and challenges from natural and human-made factors, such as climate change, pests, diseases, and cyberattacks.

Any threat to U.S. food production and security would have devastating economic, social, and political impacts. Being one of the critical infrastructures, these threats to the FA sector make it a national security issue. The current administration has recognized the importance and strength of the FA sector on U.S. security.

On 10 November 2022, President Joe Biden signed National Security Memorandum-16 (NSM-16) [42]. The purpose of the memorandum is to provide instructions to the administration on how to strengthen the security and resilience of U.S. FA to ensure that American families have access to safe and affordable food. The memorandum focuses on the threats that would prevent American farmers and producers from getting their products to the markets. The threats identified in the memorandum are the possible introduction of hazardous contaminants such as poisonous agents, natural or genetically engineered pests and pathogens, and physical effects of nuclear detonations or dispersion of radioactive materials. Other threats that are identified are current and future pandemics that could impact the sector's critical infrastructure and essential workforce, consequences of climate change, threats in the cyberdomain, and the theft of IP. The memorandum requires that a threat assessment be prepared by the attorney general and the secretary of homeland security to identify potential actors, threats, delivery systems, and methods that could be used against or affect the FA sector. Three of the threats identified in the memorandum that may result in high-consequence and catastrophic incidents affecting the FA sector are agroterrorism, climate change, and the vulnerability of the cyberdomain and how these can impact the ability of the American farmer and producers to get their products to the markets.

SECTION 02 IMPACTS OF CLIMATE CHANGE ON AGRICULTUREAL SECURITY

2.1 OVERVIEW

Among the threats identified to the U.S. FA sector, one of the most serious and potentially devastating that introduces a wide variety of vulnerabilities is climate change. Climate change is defined by the United Nations as "long-term shifts in temperatures and weather patterns. Such shifts can be natural, due to changes in the sun's activity or large volcanic eruptions" [43]. U.S. agriculture production is highly dependent on climate conditions, as the success of crops and livestock production is largely determined by the availability of water, temperature, and other weather-related factors. Climate conditions can directly affect the growth and development of crops, the health and productivity of livestock, and the availability of natural resources such as soil and water. In addition to these direct impacts, climate change can cause indirect stress on the agricultural system arising from changes in pest and disease patterns. Climate change can alter the distribution and abundance of pests and diseases that affect crops and livestock.

Climate change is not a threat of the future; it is a threat of today, and the effects are already being felt. As most remember, in the year of 2020, the United States faced the dual challenges of dealing with the impacts of climate change and the COVID-19 pandemic. In 2020, the United States faced a record 22 climate- and weather-related disasters that exceeded a billion dollars. Both crises affected the livelihoods and food security of millions of people and strained the essential services for Americans. The impacts of a pandemic and climate-related disasters "illustrates the complexity of addressing these issues" [3].

Climate change is also putting a strain on the U.S. military. It is impacting the readiness and capacity of the U.S. military to respond to humanitarian crises and natural disasters caused or exacerbated by it and is impacting the U.S. military's own infrastructure and operations from its direct impacts [44]. Additionally, it is impacting the stability of countries and regions that are vulnerable to climate-induced conflicts, displacement, famine, and disease. Climate change poses serious risks to national and global security, and it requires urgent and coordinated action from governments, militaries, and society.

To address climate change, the United States and almost 200 other countries adopted an international agreement on 12 December 2015 [45]. The agreement is a legal, binding international treaty known as the Paris Agreement. Its goal is "to limit global warming to well below 2 °C, preferably to 1.5 °C, compared to preindustrial levels" [46]. In 2020, the United States left the Paris Agreement but rejoined in 2021 [47].

To tackle the current climate crisis, President Biden created the first-ever National Climate Task Force and announced a new target of reducing its emissions by 50–52% below 2005 levels by the year 2030 [47, 48]. President Biden also announced that the United States would achieve net-zero emissions by 2050. In addition, President Biden has pledged to double the amount of U.S. international climate finances to developing countries by 2024 [48]. This includes providing $1 billion to the Green Climate Fund.

The Biden administration also highlighted the importance of addressing the climate crisis as a key priority for enhancing the security and resilience of the U.S. FA sector in the NSM-16 [42]. The memorandum recognizes that climate change poses significant risks to food production, distribution, and consumption. It calls for reducing GHG emissions from the sector, increasing carbon sequestration in soils and plants, advancing climate-smart agriculture practices, and adapting to the impacts of climate change. The memorandum also emphasizes the need to collaborate with international partners and allies to tackle the global challenge of climate change and its effects on food security.

The impacts of climate change and the nature and scope of the vulnerabilities that climate change pose on U.S. agriculture and DoD operations are discussed in this section.

2.2 HISTORICAL OVERVIEW

Over the past few decades, there has been an increase in the frequency and intensity of weather- and climate-induced events, which has resulted in decreased food harvests and increased food prices. According to the 2021 FAO report "The Impacts of Disasters and Crises on Agriculture and Food Security," from the 1970s to the 2010s, the number of disasters that include droughts, storms cyclones, hurricanes, typhoons, and extreme temperatures has increased from roughly 40 per year to more than 150 per year [2].

Farmers and the agribusiness community face serious challenges from these extreme weather events, which have become more frequent and costly in the past few decades. The United States experienced 156 weather or climate disasters that each caused more than a billion dollars in damages from 2005–2019, totaling $1.16 trillion in losses shown in Figure 2-1 [49] and a few examples included can be seen in Table 2-1.

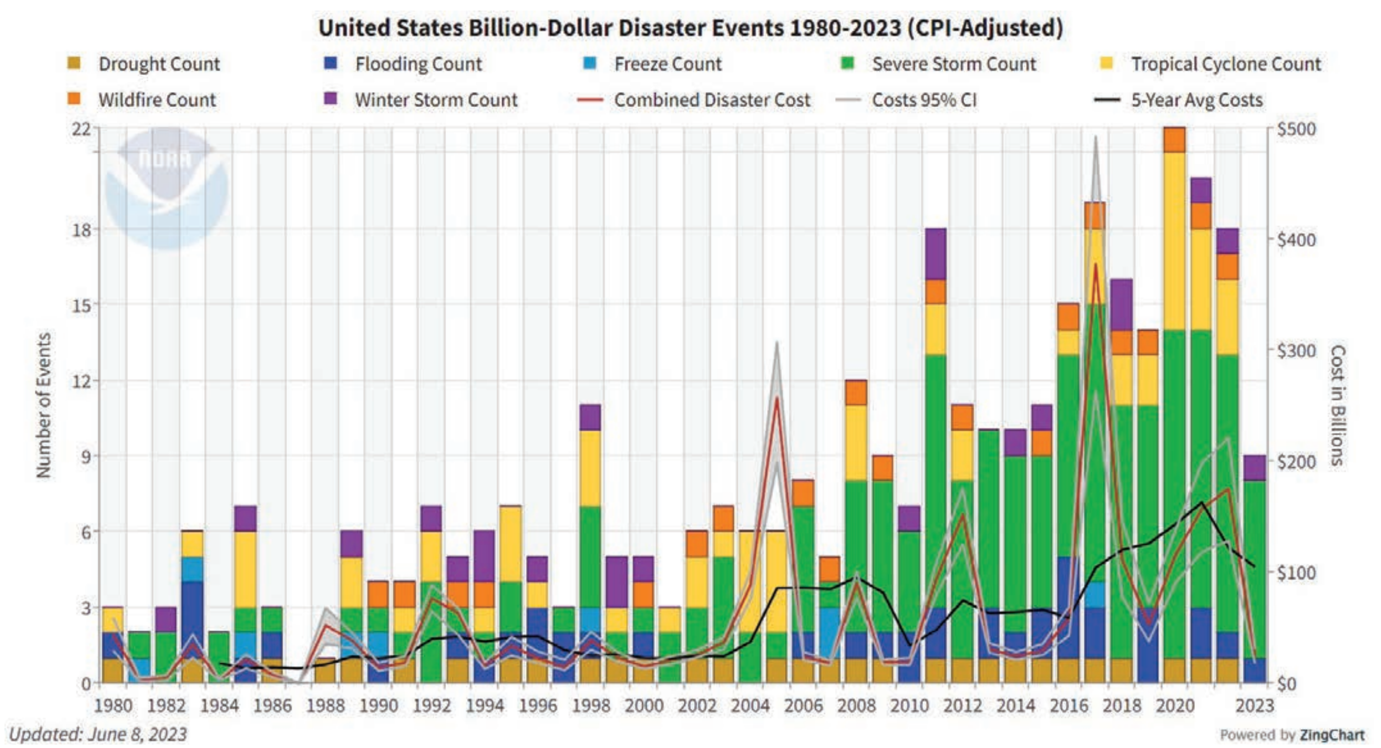

Figure 2-1. Summary of U.S. Billion-Dollar Disasters *(Source: National Centers for Environmental Information, National Oceanic and Atmospheric Administration [49]).*

Table 2-1. Examples of Severe-Weather- and Climate-Related Disasters

Year	Overview	Impact
2012	The most severe drought in 25 years severely impacted the U.S. agricultural production. Major portions of the agricultural land were damaged or destroyed in the Midwest [50].	• Affected 80% of the U.S. agricultural land and led to disaster declarations for more than two-thirds of its counties [50]. • Reduced the output of livestock and crops like wheat, corn, and soybean in the Great Plains and Midwest [50]. • Cost $14.5 billion in federal crop insurance payments [50].
2015	Drought in California	Caused [50]: • $1.84 billion in direct losses. • 10,100 fewer seasonal jobs. • 8.7 million acre-feet of surface water deficits.
2018	Wildfires in California	• Damaged crops and livestock with smoke, ash, and chemicals [51]. • Was the deadliest and most destructive year due to wildfires [52]. • Totaled over 8,500 fires burning a total of 1.9 million acres [52]. • Included calculated damages of [52]: – $27.7 billion in direct capital impact from burned buildings and homes. – $32.2 billion from the health effects of air pollution. – $88.6 billion in losses indirectly caused by the disruption of economic supply chains, including impediments to transportation and labor.
2019	In the spring, U.S. agriculture experienced a record-high number of prevented planted acres primarily due to historic rainfall across large portions of the Corn Belt and Midsouth. Producers of corn, upland cotton, soybeans, and wheat were impacted with a substantial loss of revenue due to the lack of crops being produced and marketed [53].	• Had 11.4 million acres of corn not planted [53]. • Had foregone gross revenue from crop sales that likely exceeded $6 billion alone [53].

In 2022 alone, the U.S. experienced 18 separate weather and climate disasters costing at least $1 billion, which was the third-highest number in frequency and cost for billion-dollar disasters in a calendar year behind the 22 events in 2020 and 20 events in 2021 (Figure 2-2). These include [54]:

- 1 winter storm/cold-wave event (across the central and eastern United States).
- 1 wildfire event (wildfires across the western United States including Alaska).
- 1 drought and heat-wave event (across the western and central United States).
- 1 flooding event (in Missouri and Kentucky).
- 2 tornado outbreaks (across the southern and southeastern United States).
- 3 tropical cyclones (Fiona, Ian, and Nicole).
- 9 severe weather/hail events (across many parts of the country, including a derecho in the central United States).

2.3 CLIMATE SCIENCE: AN OVERVIEW OF CLIMATE CHANGE

Climate change is a long-term change in the average weather patterns. It is mainly caused

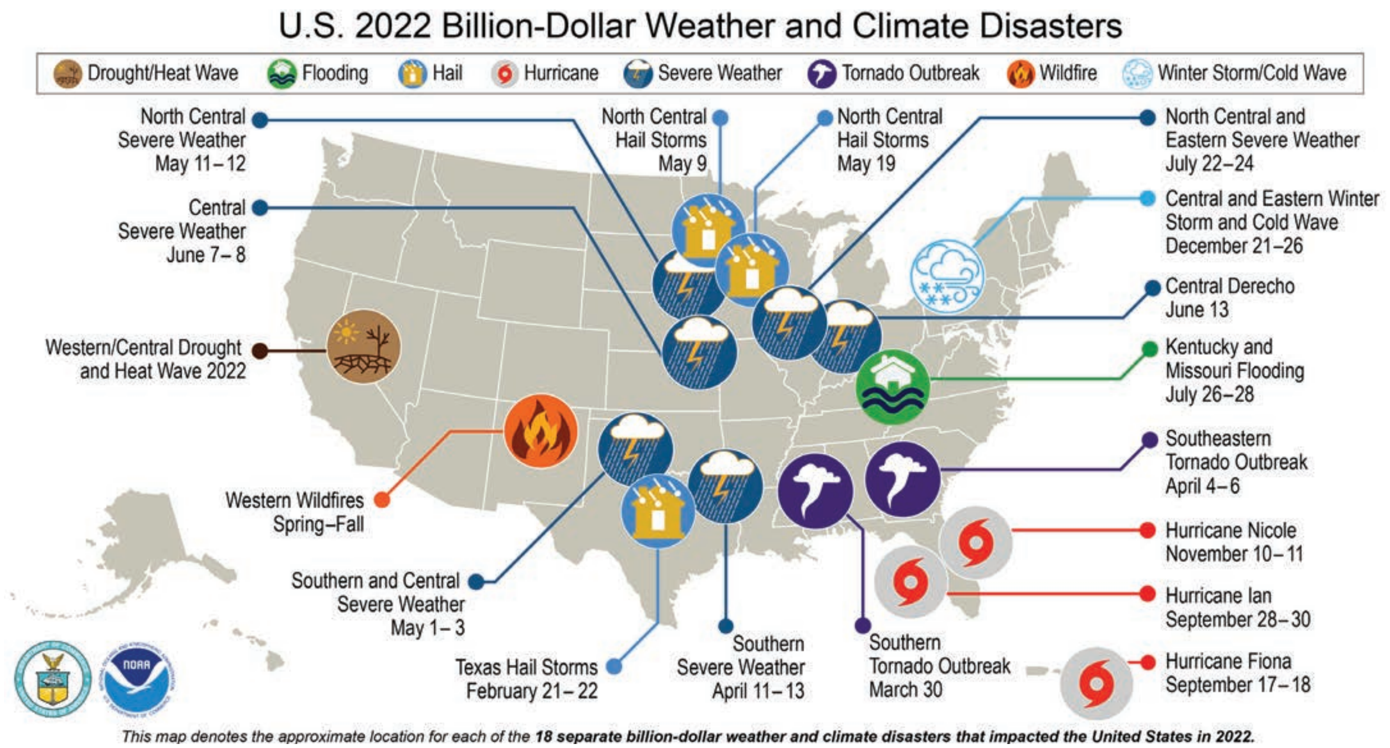

Figure 2-2. Summary of U.S. 2022 Billion-Dollar Disasters *(Source: Smith [54])*.

by the increase in GHG emissions from human activities, such as burning fossil fuels, deforestation, and agriculture [55].

These activities cause the release of GHGs, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These three GHGs are the largest individual contributors of global warming, as depicted in Figure 2-3 [55].

- CO_2 is the largest contributor to the GHGs responsible for climate change. It is central to global warming because there is so much of it, and it lasts a long time in the atmosphere. Over 35 billion tons of CO_2 are added to the atmosphere every year, mostly by burning carbon-rich fuel like coal and oil [56]. Many different industries rely on carbon-rich fuels or other processes that give off CO_2. CO_2 is stable in the atmosphere and will reflect heat for hundreds of years, meaning that, even if all new CO_2 emissions were stopped tomorrow, it would take many lifetimes before the warming effect of past emissions would fade away [56].
- CH_4 is the second-largest contributor to climate change. "CH_4 reflects about 100 times as much heat as CO_2, but its lifetime in the atmosphere is much shorter than CO_2, about 10 years" [56]. CH_4 is emitted during the production and transport of coal, natural gas, and oil. It is also emitted from livestock and other agricultural practices, from land use, and by the decay of organic waste in landfills [55].
- N_2O is the third-largest contributor to climate change. N_2O is stable and lasts about 100 years in the atmosphere. It is emitted by growing crops with the use of nitrogen-based fertilizers and combustion of fossil fuels and solid waste, as well as during treatment of wastewater [55].

GHG emissions affect the earth's climate and have many impacts on the environment and human well-being. GHG emissions trap the sun's heat and cause the atmospheric temperature to increase, which is commonly referred to as "the greenhouse effect" [57]. The warming of the Earth leads to changes in weather patterns, sea-level rises,

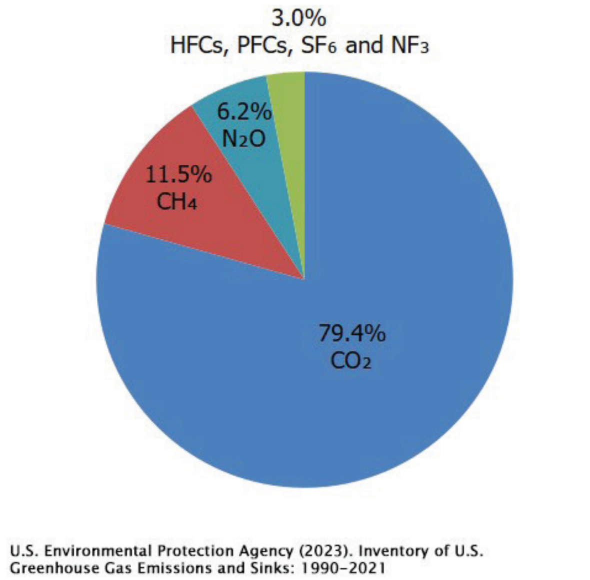

Figure 2-3. Global GHG Emissions 1990–2021 *(Source: EPA [55])*.

increase in plant and animal diseases, and more frequent and intense severe weather events (e.g., droughts, floods, heat waves, and storms), which can all lead to food insecurity.

The scientific community warns that extreme weather events will become much more likely and harder to adapt to if the global average temperature rises more than 2 °C above pre-industrial levels. The Intergovernmental Panel on Climate Change (IPCC) recommends limiting warming to 1.5 °C, which would reduce some of the impacts of climate change. However, this would require drastic and rapid changes in energy, land, urban, and industrial systems. The IPCC estimates that global net CO_2 emissions would have to drop by about 45% from 2010 levels by 2030 and reach net zero by 2050 to have a 50% chance of staying below 1.5 °C of warming [58, 59].

To address climate change, on 12 December 2015, the United States and almost 200 other countries adopted an international agreement, known as the Paris Agreement [45]. The Paris Agreement aims to limit global warming to well below 2 °C, preferably to 1.5 °C, compared to pre-industrial levels [46]. By 2030, it is estimated that temperatures will surpass the Paris Agreement threshold goal of 1.5 °C [60]. By surpassing this threshold, it is projected that 8% of plants will lose at least half of their geographic range at an increase of 1.5 °C and 16% of plants will lose at least half of their geographic range at an increase of 2 °C.

Although agriculture production systems are extremely vulnerable to changes in the climate, they are also a significant contributor to GHG emissions, accounting for 9.4% of the total emissions in the United States in 2020 [61]. The main sources of GHG emissions from agriculture are agriculture soil management (fertilizers), livestock enteric fermentation, manure management, rice cultivation, urea, and lime fertilization (Figure 2-4).

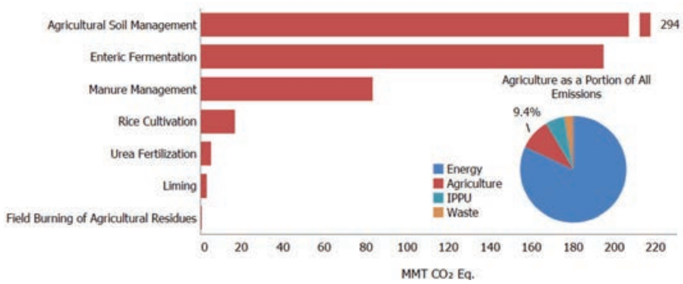

Figure 2-4. Agriculture Sector GHG Emission Sources *(Source: EPA [61])*.

Today, the United States is the second-largest emitter of GHGs in the world, after China. To address these issues, the Biden administration has taken several actions to fight climate change and lower GHG emissions. These include [47]:

- Reducing U.S. GHG emissions 50–52% below 2005 levels by 2030.
- Reaching 100% carbon pollution-free electricity by 2035.
- Achieving net-zero emissions economy by 2050.
- Delivering 40% of the benefits from federal investments in climate and clean energy to disadvantaged communities.

2.4 CLIMATE CHANGE TRENDS AND IMPACTS TO U.S. AGRICULTURE

Compared to the other 16 critical infrastructures in the United States, the FA sector is extremely vulnerable to the risks that come with climate change. Not only is U.S. agriculture production vulnerable to the direct effects of the changing climate (e.g., increasing temperature and changes in precipitation), it is also vulnerable to the indirect effects of climate change (e.g., pests and diseases) [62].

2.4.1 Trends of Climate Change

Increase in Temperature. One of the main trends of climate change is the increase in global temperature. The greenhouse effect, which is a natural process that traps some of the sun's heat in the atmosphere, is becoming stronger due to human activities that emit GHGs. This causes the Earth to warm up more than it would otherwise [63]. According to the National Oceanic Atmospheric Association (NOAA), the global surface temperature of the Earth for 2022 was the sixth highest since recordkeeping began in 1880, at 1.06 °C warmer than the pre-industrial period (1880–1900) and 0.86 °C warmer than the 20th-century average [64].

Figure 2-5 shows that "the past 9 years have been the warmest years since modern recordkeeping began in 1880" [65]. The baseline of the average global temperatures is chosen to be the average temperatures between 1951–1980, which is represented by the horizontal line at 0 °C. This was chosen to be the baseline because it takes a three-decade-long period to define "normal" or average temperatures and the analysis began in 1980. The blue bars represent cooler temperatures than average, and the red bars represent warmer temperatures than average.

An increase in temperature can have various impacts on food production and security, such as [66]:

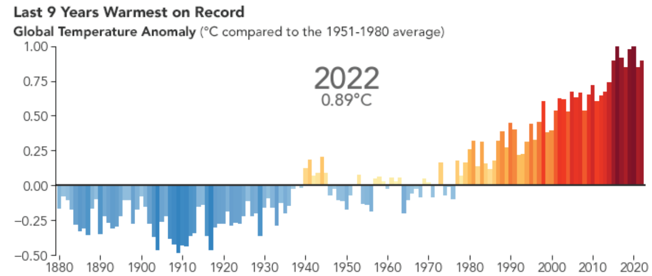

Figure 2-5. Global Average Temperature Compared With Mid-20th Century *(Source: National Aeronautics and Space Administration [65]).*

- Affecting the length and timing of the growing season, which can alter the suitability of certain crops for certain regions and affect their yield and quality.
- Affecting the water availability and quality, which can reduce soil moisture, increase irrigation demand, and affect crop growth and survival.
- Affecting the crop productivity and quality, which can reduce photosynthesis, increase respiration, alter nutrient uptake, and increase pest and disease pressure.

Change in Precipitation Patterns. Another trend of climate change is the change in precipitation patterns [67]. Global warming affects the water cycle by making the air hold more water vapor [68]. For every rise in temperature of 1 °C (1.8 °F), the air can hold 7% more water vapor [63]. This leads to more overall precipitation on Earth. However, this does not mean that all places will get more rain or snow. Some places, like the Southwest, have gotten drier because of changing weather patterns [63, 68, 69]. The average precipitation in the lower 48 states has gone up by 0.2 in every 10 years since 1901 [62]. Changes in precipitation patterns can alter the amount, intensity, frequency, and duration of rainfall and snowfall, which can result in floods or droughts that can damage crops, soil, livestock, and infrastructure [62, 63, 68, 69].

Increase in Severe Weather. A third trend of climate change is the increase in frequency and intensity of severe weather events [2, 63, 67]. Extreme weather events such as hurricanes, tornadoes, hailstorms, and blizzards can become more frequent and intense because of climate change [2, 63]. This does not mean that climate change directly causes these events, but it makes them more likely and more damaging than they would be otherwise [63]. Over the past few decades, there has been an increase in the frequency and intensity of weather- and climate-induced events. The timing and severity of these events can result in severe crop and livestock damage and increased food prices [2, 63, 67, 70].

These trends of climate change pose serious challenges for farmers and the agribusiness community, as they affect the length and timing of the growing season, the water availability and quality, the crop productivity and quality, and the pest and disease pressure [66, 71].

2.4.2 Direct Impacts of Climate Change

Heat Waves. NOAA recently conducted a study to examine extreme temperature conditions. Temperature measurements at 50 different weather locations within the United States were collected from 1961–2021. The study found a steady increase in frequency (Figure 2-6) and duration (Figure 2-7) of heat waves [72].

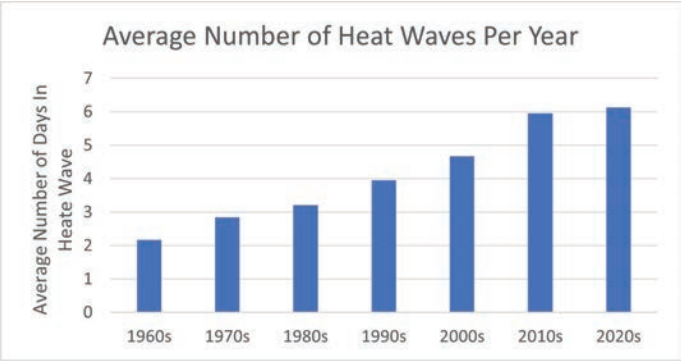

Figure 2-6. Frequency of Heat Waves: EPA's Climate Change Indicators in the United States *(Source: EPA [72]).*

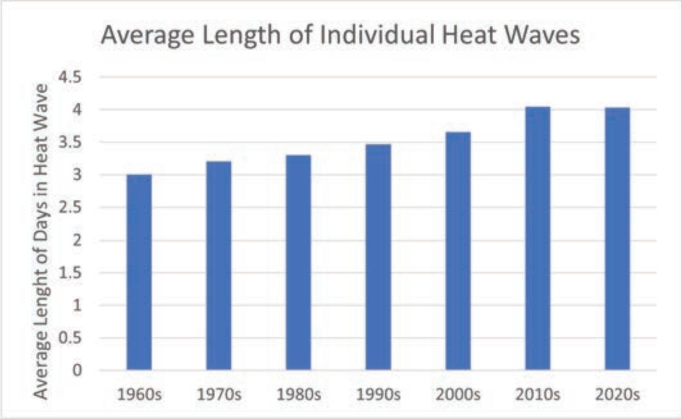

Figure 2-7. Duration of Heat Waves *(Source: EPA [72]).*

These extreme heat conditions directly impact agriculture; the yields of the four major crops of corn, wheat, rice, and soybeans are negatively impacted by exceeding temperature thresholds for optimal yields. Crops have an optimal temperature for performance, and hotter temperatures typically result in a steep decline in yields. For example, yields increase with temperature up to 29 °C (84 °F) for corn and 30 °C for soybeans, but, as temperatures start to exceed these thresholds, yields are projected to decrease, on average, by 7.4% for corn, 6.0% for wheat, 3.2% for rice, and 3.1% for soybeans [73]. Extreme heat conditions also impact the crop yields, especially during the reproductive development phase of the plant. Crops typically have a 30-day reproductive development phase, and, if extreme heat happens over a 3-day period during the reproductive phase, a 10% crop loss is typically experienced [74].

Temperature extremes also impact the health of livestock. Increases in daily maximum temperatures and heat waves will lead to heat stress for livestock. Excessive temperatures alter the physiological functions of animals, resulting in changes in respiration rate, heart rate, blood chemistry, hormones, and metabolism; such temperatures generally result in behavioral changes as well, such as increased intake of water and reduced feed intake. Heat stress also affects reproductive efficiency. High temperatures associated with drought conditions adversely affect pasture and range conditions and reduce forage crop and grain production, thereby reducing feed availability for livestock. More variable winter temperatures also cause stress to livestock and, if associated with high-moisture blizzard conditions or freezing rain and icy conditions, can result in significant livestock deaths [75].

Drought. According to NOAA's National Weather Service, drought is defined as a deficiency of moisture that results in adverse impacts on people, animals, or vegetation over a sizeable area. The FAO has established drought as the single greatest culprit of agricultural production loss worldwide, and NOAA ranks drought as the third among extreme weather events associated with billion-dollar weather disasters, behind tropical cyclones and severe storms [76].

The economic impacts of drought in the agriculture sector are crop failure and pasture loss. Specialty crops (such as fruits, vegetables, tree nuts, and medicinal herbs) are more vulnerable to drought than field crops (wheat, soybeans). These costs are often passed on to consumers through increased prices, and/or they may be offset through government disaster-assistance programs [77]. Droughts can also be expensive for consumers with increased food and energy prices, as well as be costly for the municipality, province, and country where they occur. If a drought is severe enough, it may also have an impact on the overall GDP of a nation [78].

Human-generated atmospheric CO_2 and other GHGs have made droughts longer and more frequent [79]. Between 1895 and 2010, on average, around 14% of the United States was experiencing severe to extreme drought in any given year. Notably, the Dust Bowl era affected the largest geographical area and was the longest drought in U.S. history [80].

A 2017 study identified 13 major drought episodes. The drought episodes' criteria were defined by 10% or more of the country in drought—that affected the United States between 1900 and 2014. The three longest drought episodes occurred between July 1928 and May 1942 (the 1930s Dust Bowl drought), July 1949 and September 1957 (the 1950s drought), and June 1998 and December 2014 (the early 21st-century drought). Each of these drought episodes covered 60% or more of the contiguous United States at its peak and lasted 99 months or longer [80].

The early 21st-century drought plagued many parts of the United States. These droughts combined into a national-scale event, the likes of which had not been seen in decades.

The U.S. 2012 drought event impacted 80% of agricultural land in the United States. The drought caused an economic loss of $30 billion [81], mainly affecting the agriculture sector. The drought affected the production of livestock and field crops such as wheat, corn, and soybean production in the Great Plains and Midwest. In California's agricultural sector, a result of $1.84-billion loss in direct cost was recorded [82].

In January 2013, the USDA declared 597 counties across 14 states natural disaster areas as a result of the ongoing drought that threatened the winter wheat crop. This was the second year in a row that a declaration had been made, which had not been declared since the 1950s [83].

In February 2023, the United States was experiencing drought conditions throughout the country. According to the National Integrated Drought Information System, 1,710 counties with crops were experiencing drought, along with 252.9 million acres of crops, 21.5 million beef cattle, and 646 counties [84].

Drought, in addition to water use, contributes to the depletion of groundwater systems. Groundwater is among the nation's most important natural resources. It provides half of U.S. drinking water and is essential to the vitality of agriculture. Irrigated agriculture is one of the major consumers of water supplies in the United States [75]. Groundwater that supplies the irrigated water for agriculture is supplied by two primary ground water systems in the United States—California's Central Valley Aquafer and the Ogallala Aquifer beneath the Great Plains. These aquafers are at their lowest level recorded [85]. Water from these aquifers supplies 20% of the world's grain crop; more than 40% of the nation's beef production; and about 40% of the vegetables, nuts, and fruits consumed in the United States [86].

The same aspects of climate change that affect the incidence of drought also affect the frequency and intensity of wildfires, which pose major risks to agriculture. The number of days with high fire danger occurring at the same time across large areas in the western United States has increased by 25 days since 1979. In addition, the average length of the wildfire season across the United States is 105 days longer, with three times as many large fires (greater than 1,000 acres) as in the 1970s [87]. The year of 2020 was the most active wildfire year on record. Colorado had three of its worst wildfires in history, and California recorded five of the six largest wildfires in history [88].

Across the United States, 75% of the area consumed by wildfires is in nonforested ecosystems, much of it covering rangelands and crops. Grassland, rangeland, and forest ecosystems, which support ruminant livestock production, represent more than half of the land area of the United States [87].

Flooding. As temperatures increase, there is a risk of heavy precipitation and flooding. This is due to the release of GHGs like CO_2 and CH_4 that increase global temperature [63]. As the atmosphere gets hotter, bodies-of-water temperature increase, which, in turn, leads to a rise in evaporation and atmospheric water vapor content. The higher atmospheric water content leads to an increase in frequency and intensity of heavier rainfall [89, 90]. The FAO has established flooding as the second-most devasting effect on agriculture loss worldwide. Floods pose many risks to crops. "They may be submerged in flood water, exposed to contaminants, or susceptible to mold. Some of the major concerns for crop safety are heavy metals, chemical, bacterial, and mold contamination" [91].

An analysis of historical, extreme, single-day precipitation events is found in the Fourth National Climate Assessment [75]. The events cover 1910–2017 and show that the extreme precipitation events remained steady until the 1980s but have significantly risen since then (Figure 2-8).

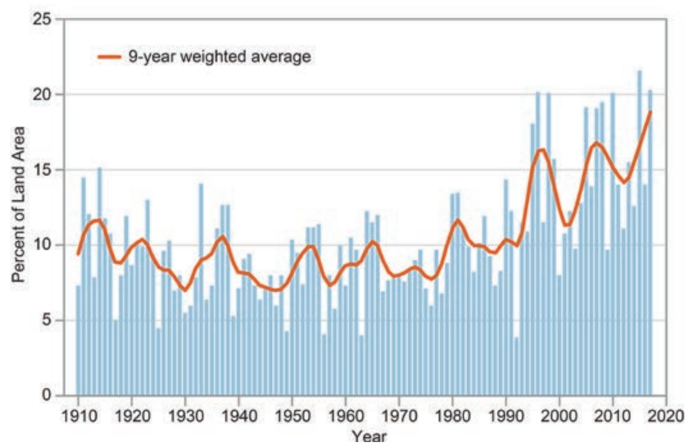

Figure 2-8. Percent of Land Area and Extreme Precipitation *(Source: Olson et al. [75]).*

Flooding on farmlands can cause many types of damage. This may include crop loss, contamination, soil erosion, equipment loss, debris deposition, and the spread of invasive species [92].

Floods can inundate farmlands and cause major damage to crops, especially if they strike during planting or harvesting season. Floods will remove significant amounts of topsoil over a large area of farming land. While some parts of the landscape will lose significant amounts of topsoil, other areas will benefit from the depositing of new topsoil [93]. In many cases, the damage from a single flood can last multiple seasons if soil health is strongly affected [94].

According to NOAA's National Centers for Environmental Information (NCEI), as of June 2023, there have been 37 weather events since 1980, where flooding was involved without a tropical cyclone or remnant that inflicted at least $1 billion of damage in the United States [95]. NCEI reports that billion-dollar inland (nontropical) flood events have increased in the United States. Most notably, four separate billion-dollar inland flood events occurred in 2016, which doubled the previous annual record, as no more than two of these events had occurred in a year since 1980. A few recent examples of floods that inflicted at least $1 billion of damages in the United States are [96, 97]:

- July 2022: Missouri, Illinois, and Kentucky, 1,000-year storm, total damage estimated at $1.5 billion.
- May 2021: Louisiana and upper Texas, total damage estimated at $1.5 billion.
- June 2016: West Virginia and Ohio, total damage estimated at $1.2 billion.
- April 2016: Houston, TX, total damage estimated at $3.3 billion.

Flooding devastated communities in Missouri and Illinois over a 3-day period from 26–28 July 2022 [98]. Over a short period of time, over a foot of rain dropped in some places. The storm was described as a 1-in-1,000-year storm. The storm took over 43 lives and resulted in over a billion dollars in damage to infrastructure, homes, businesses, and public and private property. The low-lying areas in Kentucky, which are the best land for agriculture, were damaged by the flooding and left hay fields covered with silt and debris, while livestock were washed away from the flood waters.

Coastal Flooding: Sea-Level Rise. Due to the effects of climate change, the global sea level is rising. The impacts of storms along the coast amplifies the sea levels, creating a storm surge of sea water that floods the coastal regions. Average global sea levels have risen about 8–9 in since 1880 [99]. The rising sea levels are due to a combination of melting glaciers and ice sheets and to the expansion of seawater due to increasing water temperatures. In 2021, sea levels reached 3.8 in above the average level of 1993, making it the highest annual average since 1993 [99]. Flooding is becoming more frequent along the U.S. coastlines. The East Coast shoreline experiences frequent flooding and the most flood days per year with Boston, MA, experiencing the most [100]. The Northeast Seaboard with its low elevation is losing many acres of farmland every year because of the intrusion of the seawater. Soil becomes too wet and salty to grow crops [101].

Hurricanes. Hurricanes are large, swirling storms that have winds of more than 74 mph (about 120 km/hr) [102]. Hurricanes form over warm ocean waters. The U.S. EPA has compiled hurricane data since 1878. Since 1878, on average, about 600–700 hurricanes are formed in the North Atlantic every year [102]. Historically, the frequency of hurricanes has remained constant. Since 1878, on average, 2 hurricanes have made landfall in the United States each year. In 2022, 3 hurricanes (Fiona, Ian, and Nicole) made landfall. The total number of hurricanes and the number reaching the United States have not indicated a clear overall trend since 1878 (Figure 2-9) [102].

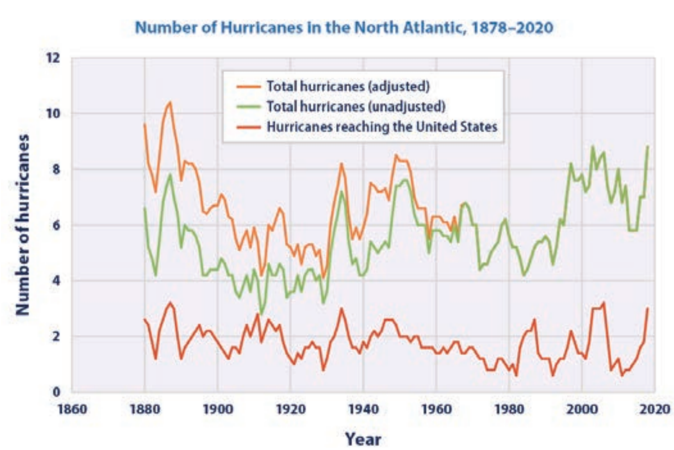

Figure 2-9. Number of Hurricanes in the North Atlantic, 1878–2020 *(Source: EPA [102]).*

When a hurricane reaches land, it pushes a wall of ocean water ashore. This wall of water is called a storm surge. Heavy rain and storm surge from a hurricane can cause flooding. The intensity of a hurricane is measured in terms of sustained windspeed and is categorized by a scale called the Saffir-Simpson Hurricane Scale. The categories are based on windspeed.

The energy of hurricanes is measured by the accumulated cyclone energy (ACE) scale. The scale is calculated by summing the square of the cyclone's maximum sustained winds and is measured every 6 hr. The scale shows an upward intensity trend of hurricanes. This trend is shown in Figure 2-10.

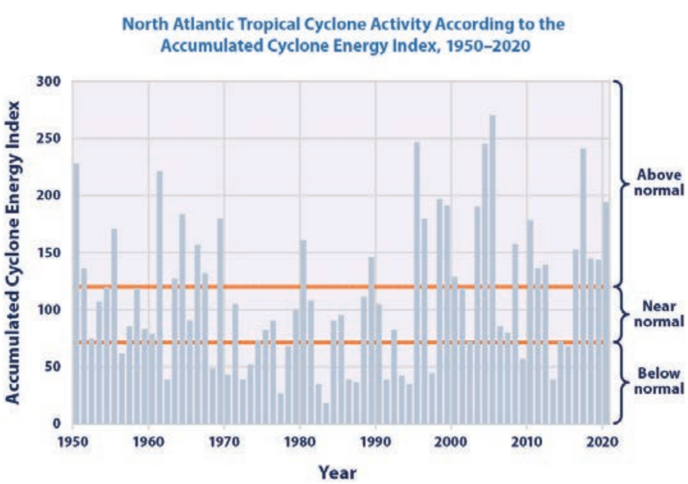

Figure 2-10. North Atlantic Tropical Cyclone Activity According to the Accumulated Cyclone Energy Index, 1950–2020 *(Source: EPA [102]).*

According to the total annual ACE index, cyclone intensity has risen noticeably over the past 20 years, and 8 of the 10 most active years since 1950 have occurred since the mid-1990s. Relatively high levels of cyclone activity were also seen during the 1950s and 1960s [102].

2.4.3 Indirect Impacts of Climate Change

Increase in Plant and Animal Diseases. Climate change can affect the distribution and severity of pests and pathogens that affect crops and livestock [103]. Higher temperatures, humidity, rainfall, and CO_2 levels can create favorable conditions for some insects, fungi, bacteria, viruses, and weeds to thrive and spread [104, 105].

Increase in Pests. Climate change can also affect the natural enemies and predators of pests, such as birds, bats, spiders, and parasitoids [106]. Changes in temperature, rainfall, wind patterns, and plant phenology can alter their abundance, diversity, and effectiveness in controlling pests [107].

Decrease in Nutritional Value of Food. Climate change can reduce the quality and safety of food by affecting the nutrient content, protein content, antioxidant levels, taste, texture, and shelf life of crops. Higher temperatures, CO_2 levels, water stress, and pest pressure can all affect these factors [108].

2.5 CLIMATE CHANGE IMPACTS ON DOD OPERATIONS

The DoD has over 5,000 military installations worldwide. Of these installations, more than 1,700 are located in coastal areas and have been or may be affected by sea-level rise or extreme weather events. Extreme weather events, along with natural disasters, have created $13 billion in damages to more than 10 DoD bases from 2017–2021. For example, in 2018, Hurricane Michael caused an estimated $4.7 billion in damage to Florida's Tyndall Air Force Base that included damage to more than 12 F-22 fighter aircraft [109]. Also in 2018, Hurricane Florence caused $3.6 billion in damage to North Carolina's Marine Corps Base Camp Lejeune. In 2021, winter storms damaged 694 facilities across four military installations in Texas (Fort Hood), Oklahoma (Fort Sill), Kansas (Fort Riley), and Louisiana (Fort Polk) [110].

The frequency and intensity of natural disasters have resulted in military humanitarian assistance both globally and domestically from civil authorities. From fiscal years 2016–2021, the number of personnel days the U.S. National Guard spent on supporting wildfires increased twelvefold, from 14,000 to more than 176,000. Over half of the approximately 450,000 National Guard members responded to natural disasters in 2022. Over 142,000 National Guard members responded to wildfires, 18,000 responded to floods, 12,000 responded to winter storms, 1,700 responded to tornadoes, and 1,000 responded to severe-weather- and other nonweather-related events [111].

The consequences of climate change increase the demands on the DoD globally and domestically. According to the Congressional Research Service, climate change could produce climate hazards such as sea or glacial ice retreat, rising sea levels, flooding, drought, extreme heat, wildfires, and hurricanes [110]. These hazards increase the risk to military operations and forces in the United States and abroad and are reshaping the geostrategic, operational, and tactical environments with significant implications for U.S. national security and defense.

2.5.1 DoD Initiatives to Combat the Climate Crisis

The DoD has identified climate change as a critical national security issue [112] and is elevating climate change as a national security priority [113]. The DoD has also noted that climate change will continue to amplify operational demands on the force, degrade installations and infrastructure resilience, increase health risks to U.S. service members, and require modifications to existing and planned equipment needs [112].

The Office of the Director of National Intelligence oversaw the development of the first-ever National Intelligence Estimate on climate change [60] and identified three risks that climate change will exacerbate [114]:

1. "Increased geopolitical tension as countries argue over who should be doing more, and how quickly, and compete in the ensuing energy transition."
2. "Cross-border geopolitical flashpoints from the physical effects of climate change as countries take steps to secure their interests."
3. "Climate effects straining country-level stability in select countries and regions of concern."

The DoD has released several policies and documents outlining how it plans to adapt to climate change. It has recognized the urgency of climate change and has adapted plans to address the impacts of climate change to its operations. The following plans have been published:

- "Department of Defense 2014 Climate Change Adaptation Roadmap" [115] outlines DoD plans on how to address climate change. The plan is a set of policies and actions that aim to address the impacts of climate change on national security, military operations, installations, personnel, and communities. The plan focuses on various actions the DoD is taking to increase its resilience to the impacts of climate change and its commitment to reduce GHGs.
- "Department of Defense Climate Risk Analysis" [116] highlights the risks of climate change and how the DoD will use the best available science and data to prevent, mitigate, account for, and respond to defense-related climate change impacts.
- "Department of Defense Climate Adaptation Plan" [117] incorporates the 2014 Climate Change Adaption Roadmap and includes more requirements, objectives, and metrics that are provided in the 2014 roadmap. The Climate Adaptation Plan (CAP) outlines the DoD's projects and activities focused on addressing climate change. Additionally, the CAP identifies several effects that will impact DoD operations to include training and testing, infrastructure, acquisition, and supply chain. The plan also

recognizes what impacts climate change will have on Defense Security Cooperation Agency humanitarian assistance and disaster response, compromised capabilities and capacity of land and sea in the Arctic regions, altered environmental conditions for military operations, and global instability.

- "Highlights and Examples: Department of Defense Climate Adaptation Plan" [118] is a companion report to the DoD CAP that provides examples of how the DoD is addressing climate change.

The DoD's focus on climate change is not new and has been addressed for decades. The DoD has made efforts to incorporate technological advances to reduce energy demand and curb GHG emissions. The White House has set a goal for the United States to achieve 50–52% reductions from 2005 levels of net GHG pollution by 2030 and for the DoD to reach net-zero GHG emissions by 2050 [47]. In fiscal year 2022, the DoD planned to allocate $469 million of military construction funds through the Energy Resilience Conservation Investment Program to fund a microgrid initiative to protect mission-critical assets and reduce GHG emissions where practicable through deployment of on-site energy storage and renewable energy generation assets [119]. The Army plans to have a microgrid on every Army installation by 2035—a number no less than 130, well above the approximately 15+ grid-tied systems currently operational across the DoD. Microgrids are an increasingly promising solution for providing the DoD with energy resilience, or the ability to provide uninterrupted electricity supply to and recovery from disruptions in power at fixed military installations [120]. Moreover, microgrids are the vision for the future of DoD installations, and their use of renewable power will help reduce GHG emissions.

2.5.2 Technologies to Combat Climate Change

Renewable energy sources are clean, accessible, affordable, sustainable, and reliable forms of energy that emit little or no greenhouse gases or pollutants into the air [121]. The DoD is focusing on using renewable energy sources and technologies such as solar, wind, biomass, biofuels, geothermal, microreactors, and power beams to tackle the climate crisis and achieve net-zero emissions by 2050. In addition to implementing mitigation efforts, the DoD is also focusing on carbon capturing technologies to remove CO_2 from the atmosphere.

Solar Power. Solar power using solar photovoltaic (PV) panels is just one of the energy sources the government is embracing to boost its energy resiliency. According to the Solar Energy Industrial Association, there are more than 130 MW of solar PV energy systems powering U.S. Navy, Army, and Air Force bases in at least 31 states and the District of Columbia [122]. The Army has plans for 55 MW of additional solar projects on military bases, as well as 13 MW of solar on the roofs of 4,700 military homes at Fort Bliss in Texas [123]. In 2023, the U.S. Department of Energy (DOE) announced as a part of the Biden administrations in-America Agenda that it will be investing "$52 million for 19 selected projects, including $10 million from the Bipartisan Infrastructure Law, to strengthen America's domestic solar supply chain and $30 million in funding for technologies that will help integrate solar energy into the grid" [124].

Wind Power. Wind turbines have been built at F. E. Warren Air Force Base in Wyoming and at the Cape Cod Air Force Base in Massachusetts. Warren's wind turbines provide about 20% of the base's electricity. Cape Cod uses its wind turbines to power its radar system, a massive energy user that tracks submarine ballistic missiles and satellites. The wind turbines save the base $1 million every year, or 50% of its electricity bill [125].

Biomass. Landfill gas is a natural byproduct of the decomposition of organic material in landfills. It is composed of roughly 50% CH_4 (the primary component of natural gas), 50% CO_2, and a small amount of non-CH_4 organic compounds [126]. The CH_4 can be captured from the landfills to generate electricity or heat. Hill Air Force Base located in Utah has constructed three generators that use CH_4 from the landfills surrounding the base [127]. The Joint Base Elmendorf-Richardson Landfill Gas Plant in Alaska is another example of a military base that turns landfill gas into energy [128].

Biofuels. The DoD has been working on developing alternative fuels for its aircraft and ships, some of which include biofuels made from algae. According to the DOE, algae-based biofuels are seen as an environmentally friendly alternative to traditional diesel fuels, which produce high levels of GHGs when they burn. The DOE has said algae holds the potential to produce billions of gallons per year of renewable diesel, gasoline, and jet fuels [129].

Geothermal. The DoD is exploring the potential of geothermal electricity as a stable and continuous power resource to ensure uninterrupted military missions. Geothermal energy is a clean and renewable source of energy that can help reduce GHG emissions and mitigate climate change. The only such facility owned by the agency is located at Naval Air Weapons Station China Lake in California, which uses conventional geothermal power that is exported to the grid. The power plant produces about 270 MW of electricity and exports it to the grid [130]. This is the only such facility that is owned by the DoD and uses conventional geothermal technology exploiting hot water and steam from underground reservoirs. The DoD is planning on building additional on-site geothermal facilities and is currently soliciting proposals [131].

Microreactors. Microreactor technology has the potential to provide benefits to the military in both domestic and overseas operations. In a DoD press release from 13 April 2022, the department stated, "A safe, transportable nuclear reactor would address this growing demand with a resilient, carbon-free energy source that would not add to the DoD's fuel needs, while supporting mission-critical operations in remote and austere environments," [132]. The 2019 National Defense Authorization Act directs the DOE and DoD to site, construct, and operate at least one microreactor at a DoD facility by the end of 2027 [132]. Project Pele, sponsored by the DoD, is a project to design a deployable nuclear reactor, and pairing microreactors with intermittent clean energy sources could provide uninterrupted, clean power to a microgrid.

As of February 2023, Project Pele is in its final stages of design. Pending design approval, the project will begin construction and hope to have the reactor turned on in 2025 at Idaho National Laboratory. Project Pele, and microreactors in general, could be a game changer for the DoD's energy needs at forward operating bases, as well as increase resiliency, decrease costs at domestic installations, and reach the goals of zero carbon emissions [133].

Power Beam. Power beam technology can also be used as a renewable energy source if the electricity that is converted into an electromagnetic beam comes from clean sources, such as solar power, wind power, or hydropower. Power beam technology can help reduce carbon emissions and support energy transition by enabling more efficient use of solar energy from space; avoiding the disruption and costs caused by cabling, wiring, or recharge landings; and transferring power from remote renewables sites such as offshore wind farms [134].

The research for power beam technology has been ongoing for decades, but it has gained more attention and investment in recent years due to the increasing demand for clean and reliable energy sources [135]. There have been several successful demonstrations of power beaming using microwaves or lasers, both on Earth and in space [136].

Carbon Capture and Storage. Carbon capture and storage is a collection of technologies that can be used to combat climate change by reducing CO_2 emissions. CO_2 generated from burning fossil fuels or captured from other large CO_2-generating processes (power, cement, steel, and chemical plants) can be captured before being released to the atmosphere and then storing the CO_2 deep underground or using it for other purposes [137]. Carbon Capture Large-Scale Pilots and Carbon Capture Demonstration Projects Program are two programs funded by President Biden's bipartisan infrastructure law that aim to significantly reduce CO_2 emissions in order to reach the president's goal of a net-zero emissions economy by 2050 [138].

- Carbon Capture Large-Scale Pilots: This program will fund up to 10 projects with up to $820 million to test new carbon capture technologies on large sources of emissions in the power and industrial sectors. The goal is to reduce the risks and costs of these technologies and attract more investments for their deployment [138].
- Carbon Capture Demonstration Projects Program: This program will fund about 6 projects with up to $1.7 billion to show how carbon capture technologies can work with CO_2 transportation and storage systems. The goal is to apply these technologies to power plants and major industrial emitters and make them more widely available [138].

As discussed, the DoD has made efforts to incorporate technological advances to reduce energy demand and curb GHG emissions. However, for the military to perform its missions and support global operations, it is vital to have secure and reliable access to energy, water, and land resources at all times [139]. The U.S. Army Office of Energy Initiatives, under the Assistant Secretary of the Army for Installations, Energy, and Environment, is working on "islandable" projects and opportunities to make this possible (Figure 2-11) [139, 140]. These islandable projects will support the military's critical operations in the event that the electric grid were to go down [139].

2.6 CONCLUSION

Climate change poses a serious threat to the national security and defense of the United States. Defense Secretary Lloyd Austin stated that "climate change is making the world more unsafe, and we need to act to keep the nation secure. The DoD must tackle the existential threat of climate change" [141].

Climate change affects the stability and security of regions where U.S. troops operate, increases the demand for humanitarian assistance and disaster relief, and impacts the readiness and resilience of U.S. military installations and infrastructure [44]. Climate change also affects the U.S. agriculture sector, which is vital for the nation's food security and economy. The U.S. agriculture sector is vulnerable to the risks of climate change, such as extreme weather events, droughts, floods, pests, diseases, and reduced crop yields. These risks can disrupt food production, distribution, and availability and increase food prices and insecurity.

The DoD has acknowledged the urgency of tackling the climate crisis and has taken steps to integrate climate considerations into its policies, strategies, and operations [142]. It has released a climate adaptation plan that outlines how it will adapt to changing climate conditions, train and equip a climate-ready force, ensure built and natural infrastructure resilience, manage supply chain risks, and enhance collaboration with other agencies and partners [143]. The DoD has also developed a climate assessment tool to understand the impacts of climate change on its installations and infrastructure [144].

In 2020, the United States experienced a record 22 climate- and weather-related disasters that exceeded a billion dollars of economic impact, which coincided with the COVID-19 pandemic.

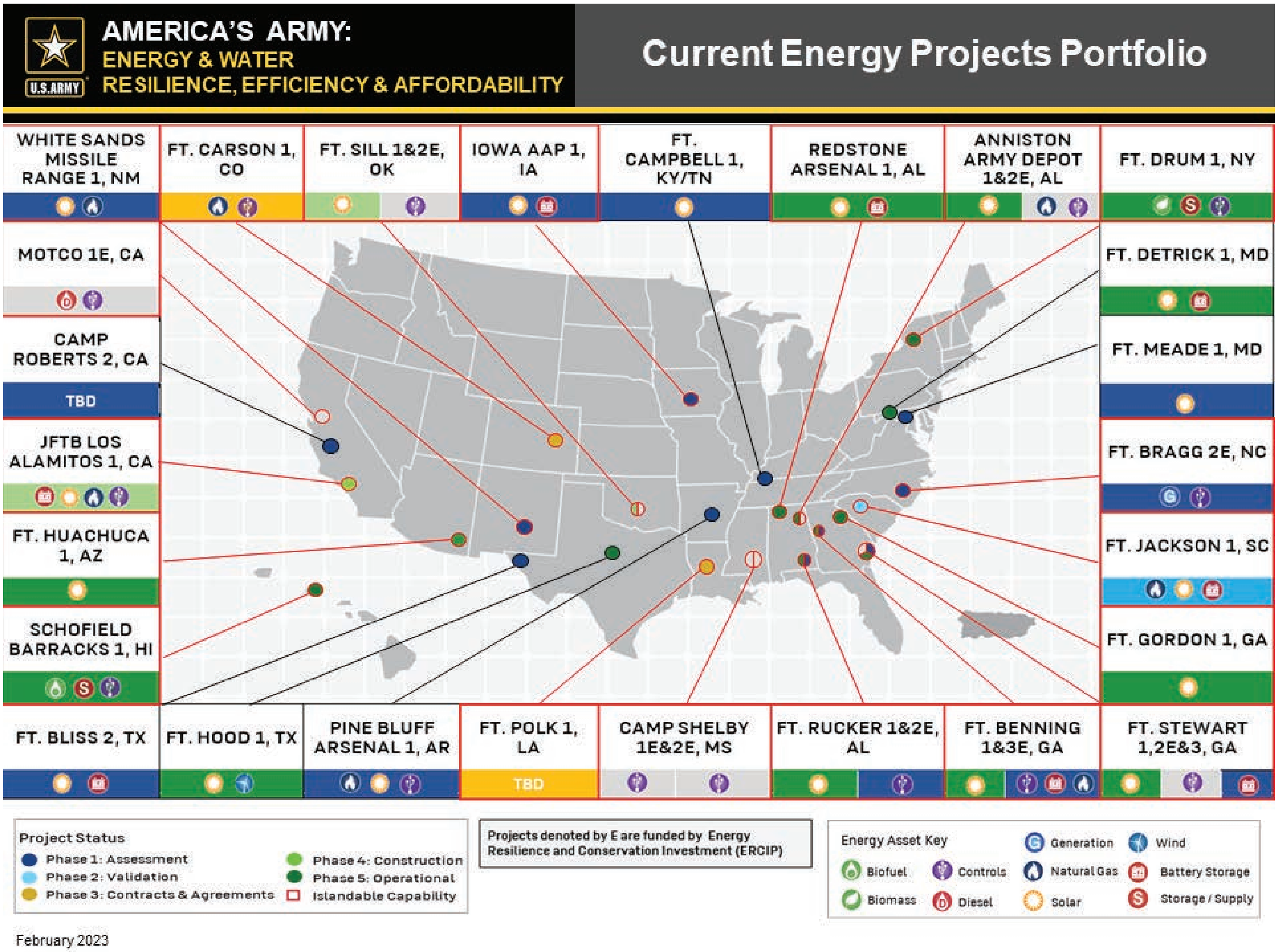

Figure 2-11. Current Energy Projects Portfolio *(Source: U.S. Army Office of Energy Initiatives [139])*.

Both crises affected the livelihoods and food security of millions of people and strained the essential services for Americans. The impacts of pandemic- and climate-related disasters "illustrate the complexity of addressing these issues" [3].

Climate change can also create or exacerbate biosecurity threats to the U.S. agriculture sector, such as the introduction or spread of pathogens or invasive species that can harm crops, livestock, or human health. These threats can have serious consequences for public health, economic stability, and national security [44].

To address the challenges of climate change while also meeting the growing demand for food due to population growth, farmers will need to find ways to increase crop yields while also reducing GHG emissions. They will need to do this while still operating their farms efficiently, sustainably, and profitably. However, by doing this, threats that come with the use of modern technologies also need to be assessed, which is discussed in Section 4.

SECTION 03 BIOLOGICAL THREATS TO AGRICULTURE

3.1 OVERVIEW

The FA sector is a key component of the national economy, national security, and way of life and serves as a strategic driver of the way of life in the United States [145]. The FA sector in the United States is vulnerable to the accidental or intentional introduction of disease agents or emerging or re-emerging diseases. Biosecurity measures have been developed to prevent and limit the severity of introduced diseases, but the potential for agroterrorism remains a challenge. The definitions of biosecurity, bioterrorism, and agroterrorism are as follows:

- Biosecurity refers to all measures (policies and practices) taken to prevent diseases and the pathogens that cause them (viruses, bacteria, fungi, parasites, and other pathogenic micro-organisms) and keep them away from livestock, property, and people. Import restrictions on animals and animal byproducts are in place to prohibit potential contaminated items into the United States. Biosecurity plans are designed to reduce the chances of an infectious disease being carried onto a farm by people, animals, equipment, or vehicles. Standard biosecurity measures for livestock farms include limiting nonessential visitors to the farm and keeping a record of all approved visitors and their previous visits to the farm and/or their contact with other animals [146]. Preparedness for an outbreak includes having tests to screen and rapidly identify infected animals. Tests used in surveillance may range from clinical observations and the analysis of production records to rapid field and detailed laboratory assays [147]. The development of rapid field tests is important for early detection of infectious diseases in animals. For example, a rapid screening test for antibodies to *Yersinia pestis* F1 and V proteins has been developed based on lateral flow technologies [148].
- Bioterrorism is the "deliberate release of viruses, bacteria, or other germs (agents) used to cause illness or death in people, animals, or plants. These agents are typically found in nature, but it is possible they could be changed to increase their ability to cause disease, make them resistant to current medicines, or increase their ability to be spread into the environment. Biological agents can be spread through the air, through water, or in food. Terrorists may use biological agents because they can be extremely difficult to detect and do not cause illness for several hours to several days" [149].
- Agroterrorism is a subset of bioterrorism and is defined as a "deliberate introduction of an animal or plant disease with the goal of generating fear, causing economic losses, and/or undermining stability" [6].

Ever since 11 September 2001 (9/11), the potential for terrorist attacks against agricultural targets (agroterrorism) has been recognized as a national security treat [6]. Several agencies, including the USDA, DHS, U.S. Department of Health and Human Services, EPA, and DoD, play a role in protecting the nation against agroterrorism.

- The USDA is responsible for protecting the nation's food supply and agricultural resources from natural and intentional threats. It conducts research, surveillance, diagnosis, prevention, response, and recovery activities related to animal and plant health, food safety, and food security [150].
- The DHS is responsible for coordinating the overall national effort to enhance the protection of critical infrastructure and key resources, including FA. It conducts threat and vulnerability assessments, develops and implements protective programs and measures, facilitates information sharing and communication, and provides grants and technical assistance to state and local partners [151].
- The Food and Drug Administration (FDA) is responsible for ensuring the safety and security of human food and animal feed. It regulates food production, processing, distribution, and retailing; establishes standards and guidance for food defense; inspects food facilities; oversees food imports; investigates foodborne outbreaks; and enforces food laws and regulations [152].
- The FBI is responsible for investigating acts of terrorism, including agroterrorism, within the United States. It collects and analyzes intelligence, conducts criminal investigations, coordinates joint terrorism task forces, provides crisis management and tactical support, and works with domestic and foreign law enforcement agencies [153].
- The role of the DoD in agroterrorism is to support the lead federal agencies in protecting the nation's FA sector from deliberate threats [154]. Some of that support includes the following:

  - Conducting research and development on biological defense, detection, identification, and decontamination technologies and countermeasures and providing medical support and expertise to prevent and respond to animal and human diseases caused by agroterrorism [155].
  - Providing logistical support and transportation assets to assist in quarantine, movement control, and disposal operations in case of an outbreak [154].
  - Providing security and force protection to critical FA facilities and assets [154].

- The U.S. Department of Health and Human Services is responsible for conducting research and development of vaccines, diagnostics, and treatments for animal and plant diseases that could be used as biological weapons. It oversees the safety and security regulations of the select agent program and provides technical assistance and guidance to state and local public health authorities on foodborne illness outbreaks and other public health emergencies related to agroterrorism [156].
- The EPA provides the regulations for the use and disposal of pesticides and other chemicals that could be used to contaminate crops, livestock, and water sources. The agency monitors the quality and safety of drinking water and wastewater systems that could be targets of agroterrorism and provides technical assistance and guidance to state and local environmental authorities on environmental contamination and remediation issues related to agroterrorism [156].

Agroterrorism has gained increased attention because of the events of 9/11, and more recently because of the increasing concerns of the continuing rapid advancements in biotechnology that could enable or facilitate the development of biological weapons and the creation of adapted harmful pathogens that could be used in terroristic attacks [157]. On 10 November 2022, the Biden administration signed NSM-16 [42] that stresses the importance of strengthening the security and resilience of the U.S. FA sector. The purpose of the memorandum is to build on the ongoing work to ensure that American families have access to safe, affordable food. The memorandum stresses the importance that the American FA system be better prepared for threats that may harm the health of crops and livestock. One of the threats identified in the memorandum is the possible introduction of hazardous contaminants such as poisonous agents, natural or genetically engineered pests, or pathogens.

3.2 PATHOGEN VULNERABILITIES TO THE AGRICULTURE SECTOR

The U.S. agriculture sector is vulnerable to the emergence of new and unknown pathogens, such as viruses, bacteria, fungi, or parasites, that can affect plants, animals, or humans [158, 159]. It has also become more vulnerable to being targeted by state and nonstate actors in the form of agroterrorism since the agriculture sector is a critical and strategic component of the nation's economy and provides products that are essential for life. Another threat is the impact of synthetic biology on agriculture. Synthetic biology is a field of science that involves modifying or creating biological organisms [160]. Although synthetic biology is being pursued overwhelmingly for beneficial and legitimate purposes such as addressing disease, remediating pollution, and increasing the yield of crops, there are potential uses that could be detrimental to humans and other species. These same advances can be used nefariously by state and nonstate actors to produce pathogens that could be used as weapons against U.S. agriculture and food supply.

Some of the vulnerabilities that make the U.S. agriculture sector susceptible to these threats are:

- Large and open pasture lands that could allow the easy introduction of plant and animal pathogens. These plants and animals are difficult to monitor and protect from intentional or accidental contamination [161].
- Limited use or not-available vaccines for highly contagious foreign animal diseases (FADs) that are not present in the United States but could be introduced by malicious actors or through global trade and travel [162].
- High concentration and movement of animals in farms, feedlots, poultry houses, and auction barns that could facilitate the spread of infectious diseases among animals and humans [161].
- Complex and interdependent supply chains that involve multiple actors and stages, such as production, processing, storage, distribution, and consumption of food and agricultural products [161].
- Unsecured water and feed systems that could be easily tampered with or contaminated by harmful substances or pathogens [163].

A new or emerging disease that affects plants or animals could be introduced into the U.S. agriculture sector by accident or on purpose. This could lead to crop failures or the need to kill millions of infected livestock, which would have serious local and national economic impacts. The social and economic effects of animal and plant disease outbreaks are significant.

One example of such an outbreak is the foot-and-mouth disease (FMD) that occurred in 2001 in Great Britain. This disease affected farms across most of the British countryside, with 2,000 cases reported [164]. More than 6 million cows and sheep were slaughtered to stop the spread of the disease. This caused a crisis for British agriculture and tourism [165].

Another example is the bird flu, also known as avian influenza. This is a viral infection that can infect birds and sometimes humans. North America is currently facing a large and unprecedented outbreak of bird flu, mainly caused by the highly pathogenic H5N1 virus. This outbreak poses serious risks to the health and welfare of wild birds and poultry [166]. The current avian influenza outbreak has resulted in the destruction of millions of birds, as well as significant losses for local farmers and higher egg prices for consumers.

A terrorist attack against the U.S. agriculture sector could strategically impact the ability as a nation to ensure the security and safety of citizens and the ability to execute military missions. An agroterrorism attack on the food supply could be both debilitating and demoralizing, thus challenging a combatant commander's ability to field an effective combat force. As was learned from the COVID-19 outbreak, the confidence in the government's ability to govern and ensure basic securities was jeopardized and the economic impacts of the pandemic had tremendous impacts on the United States and the world. The effect of a pathogen release on the FA sector could have a similar effect as the COVID-19 pandemic.

In this section, the threats of endemic and emerging pathogens and their potential impacts on the U.S. agriculture sector and ultimately the security of the United States are discussed.

3.3 PATHOGEN THREATS

Diseases that affect livestock, poultry, and crops can come from domestic or foreign sources [167]. Animal pathogens can spread easily through contact with sick animals or contaminated environments, leading to widespread disease outbreaks in livestock and poultry. These outbreaks can have severe economic and social impacts, such as reduced production, lower income for farmers and ranchers, and disruptions to the food supply chain [168]. Plant diseases, both existing and new, are influenced by factors such as climate change, global food trade, pathogen spillover, and new pathogen strains [103]. For instance, climate change affects temperature, precipitation, humidity, and wind patterns, which can change the distribution, survival, reproduction, and virulence of plant pathogens and their vectors. Climate change has been associated with the increased occurrence and severity of wheat rust diseases caused by fungal pathogens in different parts of the world.

To prevent the spread of these pathogens, surveillance systems that can detect and monitor plant and animal pathogens are needed, along with tests that can identify them quickly and accurately, and measures that can protect animals and plants from infection. Surveillance is essential for fast detection and containment of outbreaks, evaluation of control measures, and identification of new threats. Surveillance can also show the patterns, frequency, severity, impact, and changes of plant and animal diseases [163]. The USDA Animal and Plant Health Inspection Service is the main federal agency that coordinates and regulates how animal diseases are prevented, managed, and eradicated. The USDA also supports agricultural research and extension programs and works with the private sector to provide animal health products and veterinary services that help farmers deal with common animal pests and diseases [168].

Molecular diagnostics can enhance surveillance of plant and animal pathogens by improving the sensitivity, specificity, speed, accuracy, affordability, portability, scalability, and multiplexing of detection and identification methods. Molecular diagnostics are techniques that use nucleic acids (DNA or RNA) or proteins (antibodies or antigens) to detect the presence or characteristics of a pathogen [169].

3.3.1 Key Animal Diseases Impacting Livestock Health

Key priority animal diseases that do not currently exist in the United States and would have a severe impact on the U.S. economy, generate fear, and disrupt trade/exports include but are not limited to FMD, classical swine fever (CSF), African swine fever (ASF), and avian influenza. Each are highly contagious viruses that could cause up to 100% mortality or require culling 100% of infected animals, which would devastate vital U.S. livestock resources.

FMD. FMD is a severe and highly contagious viral disease [170]. The FMD virus causes illness in cows, pigs, sheep, goats, deer, and other animals with divided hooves [170]. While many countries (Africa, South America, Asia, and some parts of Europe) across the globe are dealing with FMD in their livestock populations, the United States eradicated the disease in 1929 [171]. Since the disease can spread widely and rapidly and has grave economic consequences, FMD is one of the animal diseases livestock owners dread most. It has been called "the billion-dollar disease" because of its devastating financial consequences [170, 171]. Even a single case of the disease can trigger embargoes on trade in meat products and require the large-scale culling of herds. An outbreak of FMD would impact international trade and disrupt interstate trade, as well as direct and indirect costs related to foregone production, unemployment, and losses in related businesses [170, 171]. In 2001, the United Kingdom went through an epidemic of FMD, which led to the slaughter of 6.5 million animals and a cost of $8 billion [172]. The origin of the FMD epidemic in the United Kingdom was traced back to a pig-finishing unit in Northumberland that was later moved to Essex to be slaughtered. It is believed this movement spread FMD particles to a nearby sheep farm and then subsequently spread across the farm through other infected sheep and contaminated clothing on personnel and their vehicles. Studies concluded that the infection arrived on the pig farm through infected meat. Introductions or re-emergence of diseases that mimic FMD clinically can also cause widespread disruption of animal markets, such as vesicular stomatitis virus, bluetongue virus, epizootic hemorrhagic fever virus, or Senecavirus A [170, 173].

CSF. CSF, also known as hog cholera, continues to be the most serious and destructive disease for swine. It was first reported in the United States in 1833 in southern Ohio and quickly reached epidemic levels in the early 1900s. It was not until 1960s that an effective vaccine for CSF was developed, and the virus was eradicated in the United States by 1976. CSF currently exists in many countries including nearby countries of Central and South America and the Caribbean. Several European countries have reported epidemics. The disease is endemic in much of Asia [174].

ASF. ASF is also another deadly virus with up to 100% mortality rate in pigs. It was first identified in Kenya in 1921 and has not been detected in the United States [175]. ASF has spread through China, Mongolia, and Vietnam, as well as within parts of the European Union. More recently, it has spread to the Dominican Republic and Haiti [175]. There is no treatment of vaccine for the disease. According to the World Organization for Animal Health, from January 2020 to January 2022, ASF outbreaks were reported in 35 countries or regions around the world, resulting in over a million lost domestic pigs [176]. The only way to stop this disease is to depopulate all affected or exposed swine herds. ASF is a devastating, deadly disease that could have a significant economic impact on U.S. livestock producers [175]. Scenarios have been studied to determine the economic impacts of ASF. A 2020 2-year scenario that assumes a 2-year duration of the outbreak estimates a $15-billion loss to the pig sector. Another scenario assumes the outbreak includes the feral pig population, the disease is not eliminated over a 10-year period, and it would have an economic impact of $50 billion to the pig sector [177]. China, the world's largest producer and consumer of pork, reported the first case of ASF on 3 August 2018. Within 8 months, the disease spread to all of China's mainland provinces and caused a substantial loss to its hog industry. The supply of pork domestically fell to 21% of its pre-ASF levels, resulting in a doubling of the domestic pork prices [178].

Highly Pathogenic Avian Influenza (HPAI). HPAI viruses cause severe disease and high mortality in infected poultry. Two different outbreaks of avian influenza (bird flu) have affected the U.S. poultry industry and wild birds in recent years. The first outbreak occurred from 2014–2015 and involved North American lineage viruses that reasserted and included H5N2 and H5N8 [179]. These viruses were mainly detected in wild birds but also caused more than 200 outbreaks in commercial poultry flocks and resulted in the death or depopulation of more than 50 million birds [180]. The second outbreak has been ongoing since 2022 and involves Asian lineage viruses that are being spread by wild birds. The most prevalent virus is H5N1, which has decimated wild bird populations and contributed to the mass deaths of millions of poultry [181]. This outbreak has been found in 47 states (poultry) and has affected more than 833 commercial and backyard flocks and more than 58.7 million birds as of 17 May 2023 [182, 183]. Additionally, this outbreak has appeared to spill over into mammals (nonhuman) on several occasions and has caused one human infection in the United States after exposure to infected birds [184, 185]. The overall economic impact of the current avian flu outbreak is yet to be determined. As a result of recurrent outbreaks, U.S. egg inventories were 29% lower in the final week of December 2022 than at the beginning of the year. By the end of December 2022, more than 43 million egg-laying hens were lost to the disease itself or to depopulation since the outbreak began in February 2022 [186].

3.3.2 Key Plant Diseases Impacting Crop Health

Citrus Yellow Vein Clearing (CYVC). CYVC is an emerging disease causing escalating economic losses in multiple citrus species and varieties, especially lemons. The disease was recently detected in Tulare, CA, in 2022, which is the first detection of this disease in the United States. The disease origins are in the Asian countries, and it is spreading rapidly. The disease severely affects tree growth and fruit yield and is spread by insects or by contaminated tools. There is currently no treatment for the disease [187].

Citrus Greening. Also known as Huanglongbing (HLB), citrus greening is the most devastating disease of citrus. The Asian citrus psyllid (Diaphorina citri), which arrived in Florida in 1998, spreads the disease. The psyllid infects the tree with bacteria when it feeds on new shoots. There is no treatment for this disease, and all types of citrus can get HLB [188].

Soybean Cyst Nematode (SCN). SCN is a tiny worm that lives and feeds on the roots of soybeans, causing them to grow poorly, turn yellow, and produce less. It is the worst soybean pest in the United States, costing about $1.5 billion in losses every year. SCN can be moved from one place to another by soil, plants that host the worm, and cysts that are the remains of the female worms. To increase yields of soybeans, crops are rotated, or a soybean plant can be resistant to the nematode [189].

Fusarium Oxysporum f. sp. Cubense (Foc) Tropical Race 4 (TR4). Foc TR4 that causes Panama disease of bananas threatens to reduce the availability of bananas in some areas of the world. The TR4 strain has moved from Asia into Mozambique and Jordan and, in 2019, Colombia [190]. The disease threatens farms of both subsistence farmers in Asia and Africa and major banana plantations. Cavendish bananas, a key food source for many smallholder farmers, are threatened by TR4 [190].

Aspergillus Flavus. According to an article by North Carolina State University, Aspergillus flavus produces the mycotoxin known as aflatoxin on a number of crops including corn. Aflatoxins and fumonisins are mycotoxins produced by Aspergillus flavus and Fusarium verticillioides, respectively, that commonly contaminate corn in the southeastern United States [191]. These mycotoxins pose significant health risks to both humans and animals and are therefore regulated by the FDA.

3.4 INTENTIONAL THREATS (AGROTERRORISM)

The literature has extensively documented the threat of a terrorist act against agriculture. Although agroterrorism attacks in the United States have been relatively rare, they still pose a threat to national security and public health. Agroterrorism attacks can target any part of the farm-to-fork continuum, such as crops, livestock, or food products, as well as the transportation or distribution systems that move them from the farm to the consumer [167]. Farmland and ranches are vulnerable to such attacks because they are large and open, making them easy targets for any extremist group or adversarial nation that wants to introduce a biological disease into the U.S. agricultural system. The main motivations and goals of agroterrorism attacks include creating fear and panic, causing economic damage, disrupting operations/trade, and gaining access to agricultural commodity production and capacity [167].

The FBI identifies the top likely perpetrators as "(1) domestic/international terrorists, (2) state-sponsored insurgent/extremist elements, (3) state-sponsored weapons of mass destruction programs, (4) economic espionage by corporate- or state-sponsored competitors, (5) insider threats, [and] (6) an individual 'lone wolf'" [192].

One of the challenges with agroterrorism is that it is hard to recognize and detect an attack. An attack may go unnoticed for days or weeks, which would allow the pathogen to spread [167, 193]. Although several nations and governments have had the capability of using anti-agricultural weapons, there are only a few historical examples of intentional state-sponsored attacks against agricultural production. Some examples are as follows:

- During World War I, Germany used biological warfare agents for sabotage and infected more than 3,500 horses with anthrax and glanders that were being shipped to the allies. They targeted horses because they were essential for the military to move, fight, and survive [194, 195]. Germany also sabotaged French cavalry horses, Romanian sheep, and Argentinian livestock intended for the Allied forces [196].
- In the 1940s, the United Kingdom produced large quantities of cattle cakes that were infected with anthrax spores that could be dropped on to the fields where the cattle herds grazed [196].
- During the Cold War era, the U.S. military bioweapon programs used chemicals to destroy vegetation. It also used herbicides during the Vietnam War to destroy vegetation. The main goal of using the herbicides was to destroy the vegetation that was used as cover, but the United States also targeted crops that were used by the Viet Cong to support operations [167].

The 1925 Geneva Protocol prohibits the use of chemical and biological weapons in war [197]. The ban was later strengthened in 1972 by the adoption of the Biological Weapons Convention (BWC), which prohibited the development, production, stockpiling, and transfer of such weapons [198]. The convention has reached almost universal membership, with 184 state parties and four signatory states. The effectiveness of the BWC has been limited due to insufficient institutional support and the absence of any formal verification regime to monitor compliance.

The U.S. Department of State published an unclassified report in June 2022 on how the United States and other nations followed and complied with arms control, nonproliferation, and disarmament agreements and commitments in 2021 [199]. The president is required to prepare and release this report by the Arms Control and Disarmament Act, as amended (22 U.S.C. § 2593a) [200]. The report covers the following:

- How the United States complied with arms control, nonproliferation, and disarmament agreements in 2021 [199].

- How other nations complied and adhered to arms control, nonproliferation, and disarmament agreements and commitments, including confidence and security-building measures and the Missile Technology Control Regime, of which the United States is part [199].

Part IV of the report reviews the compliance with and adherence to arms control, nonproliferation, and disarmament agreements and commitments pertaining to biological issues. The report focuses on state biological programs that are in violation of the BWC that was put in force in 1975. Peoples Republic of China, Islamic Republic of Iran, The Democratic People's Republic of Korea (North Korea), and The Russian Federation (Russia) were all found to be in violation of the Article I of the BWC [199]. Article 1 requires state parties:

> *…never in any circumstances to develop, produce, stockpile, or otherwise acquire or retain…[microbial] or other biological agents, or toxins whatever their origin or method of production, of types and in quantities that have no justification for prophylactic, protective, or other peaceful purposes [199].*

A nation might send an agent to spread FMD throughout the United States in an act of revenge for economic sanctions that have been imposed for the invasion of Ukraine, or China could impose economic sabotage against the United States by smuggling some FMD-infected pigs into the country. China could cause the U.S. swine export trade to come to halt and then use its own pig sector to fill in the market gap that would be created by a worldwide pig export ban imposed on the United States.

The U.S. agricultural sector could also face a threat from criminal or terrorist groups. These groups may target the FA sector to cause economic disruption and social panic among the U.S. population. This has happened before in the following historic examples:

- In 1984, a religious cult contaminated 10 local restaurants with salmonella, which infected 751 people, 45% of whom needed hospitalization. The cult may have done this to influence a local election [161].
- In 1996, a worker at a rendering plant in Wisconsin called the police and said liquid fat from the plant had been contaminated with chlordane. The contaminated fat reached feed manufacturers, followed by 4,000 farms in Wisconsin, Michigan, and Minnesota. No humans or animals were harmed, but disposing of the contaminated feed cost $4 million [193].
- In October 1996, a former laboratory employee admitted to contaminating a tray of doughnuts and muffins with Shigella dysenteriae Type 2, a foodborne pathogen. The former employee at St. Paul Medical Center (in Dallas, TX) used a supervisor's office computer to email 45 other laboratory workers that pastries were available in the break room. Twelve of them ate some pastry and got severe gastrointestinal disease. Four of them had to be hospitalized, but no one died. The pathogen came from the laboratory itself, which had poor security and good conditions for the pathogen to grow [201].

It is possible for terrorists with little expertise to obtain infectious agents and infect animals. Various actors, such as transnational groups, economic opportunists, domestic extremists, or disgruntled individuals, could use agroterrorism to threaten the U.S. economy and national security. They could obtain infectious agents easily and infect animals on farms or other locations. An attack using a virus like FMD could cause serious damage to the agriculture sector and trigger civil unrest and panic.

FMD is a viral disease that affects animals with cloven hooves. It has been eradicated in the United States since 1929, but it still exists in many other countries. FMD is highly contagious and can spread through contact with infected animals or objects, as well as through the air, water, soil, feed, or animal products [202]. It can survive for long periods of time in the environment or in animal remains. FMD has an incubation period of 3–8 days, during which an infected animal may not show any signs or symptoms but can still infect others [203]. It does not affect humans, so a terrorist can handle and disperse the virus safely. A terrorist could introduce FMD into feedlots, auctions, farms, or water systems, where it could cause widespread outbreaks and devastating impacts on the agricultural sector.

The DoD states that an agroterrorism incident involving FMD is a serious threat to U.S. national security [204]. Another viral disease that poses a similar threat is ASF, which causes high mortality in pigs and has no vaccine or treatment available. ASF is currently affecting several countries around the world and could be easily accessed by terrorists.

Beyond vulnerabilities to animal health from the introduction of FADs, the FADs produce logistical challenges for combatant commanders who may have troops and equipment positioned in regions that are FAD positive when they need to rapidly deploy them to regions where those diseases have not been previously reported or risk introduction of an FAD with significant political impact [205].

Military operations in countries that are infected with FADs can expose the troops and their equipment to the risk of infection or contamination by the disease agents. This can affect the health and performance of the troops and their animals and require medical or veterinary intervention or quarantine measures.

Agroterrorism also has implications for military operations in foreign countries that are infected with FADs. Troops and equipment deployed in such regions may be exposed to infection or contamination by FAD agents, which could affect their health and performance and require medical or veterinary intervention or quarantine measures. Moreover, troops and equipment returning from such regions may pose a risk of introducing FADs into the United States or other nonaffected countries, which could have serious consequences for animal health, food security, economy, and national security. For this reason, the military enforces a strict washdown of all equipment when operating in foreign areas, whether for contingency operations or peacetime training.

3.5 SYNTHETIC BIOLOGY THREATS

Synthetic biology is a field of science that involves modifying or creating biological organisms for various purposes [206]. One of these purposes is to increase agricultural production and improve crop nutrition, which are essential for food and agricultural security. However, synthetic biology also poses potential risks, as state and nonstate actors could use it to produce pathogens that could be used as weapons against U.S. agriculture and food supply systems. These pathogens could be derived from existing organisms or created from scratch using gene-editing tools [206].

Genetically modified organisms (GMOs) are organisms (i.e., plants, animals, or microorganisms) whose DNA has been altered in a way that does not occur naturally by mating and/or natural recombination [207]. GMOs are usually made by inserting foreign DNA into an organism's genome. There are two main methods to produce GMO plants: (1) agrobacterium-mediated genetic transformation and (2) biolistics.

Agrobacterium-mediated genetic transformation uses a type of bacteria that can transfer selected genes into plant cells [208]. The plant cells then grow into transgenic plants that have the desired DNA from other species. The seeds produced by these plants will also have the new DNA. Biolistics uses a device that shoots tiny particles coated with the desired gene into plant cells. The plant cells then grow into transgenic plants that have the desired DNA. Both methods have been used to create genome-edited crops, such as corn, cotton, soybean, and wheat. Genetically modified (GM) crops have many benefits, such as increased yield, improved quality, reduced pesticide use, and enhanced resistance to pests and diseases [208].

Some examples of GMO crops are corn and cotton that have been modified with Bacillus thuringiensis (Bt), a soil bacterium that produces proteins that are toxic to some insects but not to humans [209]. Bt has been used as an insecticide for a long time, but, by inserting its genes into plants, the plants can produce their own insecticide and become resistant to insect pests. Bt corn and cotton have been approved by the EPA in the United States since 1995 [209].

Another example of a GMO crop is papaya that has been modified to resist ringspot virus, a disease that can destroy papaya plants [210]. The GM papaya has a viral gene that protects it from infection. There is no other way to control ringspot virus effectively, either organically or conventionally. The GM papaya has increased the yield of papaya by 10 to 20 times compared to non-GM papaya. The GM papaya is now grown by nearly all Chinese and Hawaiian papaya farmers [206].

GMO crops are very common in today's food supply, especially in the United States, where most of the corn, soybeans, sugar beets, canola, and cotton are GMOs. These crops are used as ingredients in many processed foods. GMOs are found in much of the western food supply due to ingredients derived from GM crops [211].

GMO animals are less common, but some have been approved for human consumption. For example, the AquAdvantage Salmon is a GM salmon that grows twice as fast as a normal salmon because it has a gene from another salmon species and a gene from an ocean pout. The FDA has stated that this fish is safe to eat [212].

Gene-editing tools are used to make changes to the existing genetic material of an organism. Unlike GMOs, which introduce foreign DNA from other organisms, gene-editing methods modify the native DNA in ways that can have beneficial outcomes.

There are different types of gene-editing methods, such as zinc finger nucleases, transcription activator-like effector nucleases, and clustered regularly interspaced short palindromic repeats (CRISPR-Cas9) [213]. CRISPR-Cas9 is the most widely used method. It allows researchers to remove, insert, or change sequences of DNA in almost any organism. This can result in the activation or deactivation of a gene, which can affect the traits of the organism. For example, a gene that makes a crop or livestock more vulnerable to disease or drought can be deactivated using CRISPR-Cas9 [214].

CRISPR-Cas9 has been used to create plants with improved traits, such as virus-resistant cucumbers, disease-resistant citrus trees, and high-yield rice lines [215]. It has also been used to manipulate animals with desirable characteristics, such as cashmere goats with longer hair fibers, cattle with increased muscle mass, and mushrooms with delayed browning [212].

Gene-editing tools like CRISPR-Cas9 can also be used to introduce genetic traits, which can be inherited by their offspring, into organisms. This can be done by editing reproductive cells, fertilized eggs, or embryos. These genetic traits can then spread through future generations using a mechanism called gene drive [216]. Gene drive is a process that increases the likelihood of a certain gene or allele being passed on to the next generation over the natural or wild-type gene or allele. Gene drive can be used to control pests or diseases that affect agriculture. For example, gene drive has been used to target Drosophila suzukii, a fruit fly that damages fruit crops such as berries, cherries, plums, and grapes [217].

Synthetic biology also poses potential risks to biosecurity and biosafety, as some of the products or techniques could be misused for malicious purposes. For example, state and nonstate actors could use genetic-editing tools to create or modify pathogens and develop novel biological weapons. They could alter the characteristics of a disease, such as how contagious, deadly, or persistent it is. They could also target agriculture and food supply systems with these weapons. However, such attacks would require advanced skills, technology, infrastructure, and planning that only state-sponsored actors could provide.

One of the factors that facilitates synthetic biology threats is the availability of open-access publications that share scientific information and knowledge on synthetic biology and molecular biology. Most of the research on synthetic biology and molecular biology is funded by the National Institutes of Health (NIH), which supports studies on pathogenic mechanisms and disease prevention. However, this also means that sensitive data and methods are generated and disseminated by researchers who may not be aware of the potential dual-use implications of their work [159].

Another factor that contributes to synthetic biology threats is the lack of secure funding for academic researchers and their trainees, who are often under pressure to publish their research for career advancement and recognition. This may lead them to accept funding from dubious sources, such as foreign governments or organizations that have malicious intentions or agendas. It may also make them more vulnerable to recruitment by hostile actors who offer them better financial prospects or incentives. Moreover, the drive to publish research may also result in the disclosure of theoretical guidelines or protocols that could enable others to replicate or modify synthetic biology experiments or products [163].

Another threat is computer hacking by gaining unauthorized access or manipulation of computer systems or networks that store or process synthetic biology or bioengineering data or software. This could result in data theft, sabotage, or cyberattacks that could compromise the security or functionality of synthetic biology or bioengineering systems or products [163].

The U.S. government has taken steps to ensure that the synthetic biology laboratories are compliant in their research. Compliant labs are labs that follow the rules and guidelines for conducting synthetic biology or bioengineering research in a responsible and ethical manner. However, even compliant labs may pose a risk if they publish or have dual-use knowledge or data that could be used by state-sponsored agroterrorists. Compliant labs may unintentionally provide state-sponsored agroterrorists with the information or tools they need to carry out their attacks, such as how to create or modify a plant or animal pathogen using synthetic biology or bioengineering techniques. The NIH provides policies and practices for the identification and oversight of dual-use research of concern (DURC) within its intramural research program. It also provides educational tools and resources for researchers and institutions to raise awareness and responsibility for DURC [163, 218].

3.6 POLICY AND REGULATIONS

The U.S. oversight of synthetic biology is based on existing regulations that cover the products and processes of biotechnology, such as the "Coordinated Framework for Regulation of Biotechnology" [219]. This regulation was proposed in 1984 by the White House Office of Science and Technology Policy and finalized in 1986. It spells out the basic federal policy for regulating the development and introduction of products derived from biotechnology. In 2017, the federal government updated the policy and produced a comprehensive summary of the roles and responsibilities for agencies with respect to regulating biotechnology [220]. The coordinated framework assigns regulatory responsibilities to three principal agencies: (1) the EPA, (2) the FDA, and (3) the USDA. Each agency regulates biotechnology products under its existing statutory authority and according to its specific mandate. For example, the EPA regulates biotechnology products that may have an impact on the environment, such as pesticides and microorganisms. The FDA regulates biotechnology products that may affect human or animal health, such as food, drugs, and medical devices. The USDA regulates biotechnology products that may pose a risk to plant health or animal health, such as genetically engineered crops and animals.

"Guiding Principles for Biosafety Governance: Ensuring Institutional Compliance With Biosafety, Biocontainment, and Laboratory Biosecurity Regulations and Guidelines" was prepared on behalf of the Federal Experts Security Advisory Panel in September 2017 [221]. It provides several guiding principles and best practices for ensuring that institutions have appropriate organizational and governance structures in place to establish compliance with biosafety, biocontainment, and laboratory biosecurity regulations and guidelines. The document also provides an overview of the federal regulations, requirements, and guidelines that pertain to biosafety and biosecurity in the U.S. and a description of some of the voluntary laboratory accreditation systems.

"Proposed Biosecurity Oversight Framework for the Future of Science" is a report by the National Science Advisory Board for Biosecurity (NSABB) that was delivered to the U.S. government on 27 January 2023 [222, 223]. It contains the findings and recommendations of two NSABB working groups that evaluated the effectiveness of two major U.S. biosecurity policy frameworks governing research with enhanced potential pandemic pathogens and DURC. The report aims to inform U.S. government policy evaluations and the development of detailed guidance toward a more comprehensive and integrated framework for the oversight of research that may pose significant biosafety or biosecurity risks. The report also seeks to ensure that U.S. biosecurity efforts are positioned to keep pace with an evolving scientific enterprise.

The Federal Select Agent Program was developed to safeguard pathogens by limiting the ability to access them and use them for harm [224]. The "Public Health Security and Bioterrorism Preparedness and Response Act of 2002" provides for the regulation of certain biological agents and toxins that have the potential to pose a severe threat to human, animal, and plant health or to animal and plant products [225]. The Federal Select Agent Program is jointly comprised of the Centers for Disease Control and Prevention/Division of Select Agents and Toxins and the Animal and Plant Health Inspection Service/Division of Agricultural Select Agents and Toxins [224]. It was established in response to a U.S. congressional mandate to ensure the safety and security of biological select agents and toxins. The Federal Select Agent Program oversees the possession, use, and transfer of biological select agents and toxins. These select agents and toxins have the potential to pose a severe threat to public, animal, or plant health or to animal or plant products. The select agents and toxins, listed in 9 CFR 121.3, are those that have been determined to have the potential to pose a severe threat to animal health or animal products [226]. The select agents and toxins listed in 7 CFR 331.3, are those that have been determined to have the potential to pose a severe threat to plant health or plant products [227].

The Federal Select Agent Program publishes an annual report that summarizes aggregate program data in areas such as [224]:

- Numbers and types of registered entities, as well as amendments to registrations.
- Top registered select agents or toxins.
- Security risk assessments performed.
- Number of inspections conducted.

- Key observations related to inspection findings and compliance with the select agent regulations.
- Reported thefts, losses, and releases of select agents or toxins.
- Identifications and transfers of select agents or toxins.

It also reports the number of individuals that have access to the select agents and new approved applicants. Risk assessments are conducted on individuals to determine acceptance into the program. The report identifies the number of inspections performed during the year and identifies any compliance issues.

3.7 CONCLUSION

The U.S. FA sector is vital for the nation's economy, security, and way of life, but it also faces various threats from natural and human-made factors. One of the most serious and potentially devastating threats is agroterrorism, which is the deliberate introduction of an animal or plant disease for the purpose of generating fear, causing economic losses, or undermining social stability [6]. Agroterrorism has gained increased attention in recent years due to the events of 9/11, the advancements in biotechnology, and the emergence of new and unknown pathogens [157]. The Biden administration has recognized the importance of strengthening the security and resilience of the U.S. FA sector and has issued NSM-16 that identifies some of the possible hazards [42].

The DoD could be affected by an agroterrorism event or an unintentional release of a plant or animal pathogen in several ways:

- Disruption of the food supply and availability for military personnel and their families, both at home and abroad.
- Public health risks to military personnel and their families, especially if the pathogen is contagious to humans or causes foodborne illnesses.
- Impairment of the readiness and operational capabilities of the military forces, especially if the pathogen affects animals used by the military, such as dogs, horses, or mules.
- Creation of a humanitarian crisis and a need for military assistance and intervention in affected regions.
- Undermining of the national security and economic interests of the United States and its allies, especially if the pathogen is used as a weapon by adversaries or terrorists.

Therefore, it is imperative that the DoD takes proactive measures to prevent, detect, respond to, and recover from agroterrorism events or unintentional releases of plant or animal pathogens that could jeopardize the security and resilience of the U.S. FA sector and the well-being of military personnel and their families.

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SECTION 04 CYBERSECURITY AND SMART FARMING

4.1 OVERVIEW

Climate change, natural resource depletion, soil erosion, and the growing population makes meeting the demands of global food production more challenging. This has led farmers to rethink the traditional agriculture methods and move toward applying the use of modern agriculture technologies and the internet of things (IoT), often referred to as "smart farming," to help increase yields, reduce labor, and reduce the costs associated with food production. The term smart farming focuses on providing the agricultural industry with the infrastructure to leverage advanced technology—including IoT, big data, the cloud, artificial intelligence, satellites, etc.—for tracking, monitoring, automating, and analyzing operations [228]. While the use of these technologies has many advantages in helping farmers make critical decisions, the adaptation introduces new cybersecurity vulnerabilities and cyberthreats with IoT [229].

Currently, there are more than 2 million farms in the United States. Family farms remain a key part in U.S. agriculture and account for 98% of all U.S. farms and 88% of total production. Most of these farms are small, family farms that only account for a small percentage of total production. Almost half of the total production comes from the large-scale, family farms, which only account for 3% of the total farms in the United States [230].

Smart farming, like any other technological system, can have a single point of failure. Since most of the production is dominated by a relatively small number of large food corporations, it makes the food supply chain vulnerable and enhances the importance that the FA sector acknowledge these vulnerabilities and therefore update its cyberprotection policies and procedures [231]. A cyberattack on one of these large food corporations could shut down food production, leading to an increase in food insecurities and major economic losses.

In April of 2022, the cyberdivision of the FBI released a notice alerting the FA sector that it could become a target of ransomware attacks during the busiest time of year after noticing a recent surge in cyberattacks on agriculture companies [232]. It was stated that: "Initial intrusion vectors included known but unpatched common vulnerabilities and exploits, as well as secondary infections from the exploitation of shared network resources or compromise of managed services." It is important now more than ever that the security issues that come with the development of agriculture incorporating modern information technologies are not ignored.

> *The FBI is informing FA sector partners that ransomware actors may be more likely to attack agricultural cooperatives during critical planting and harvest seasons, disrupting operations, causing financial loss, and negatively impacting the food*

supply chain. The FBI noted ransomware attacks during these seasons against six grain cooperatives during the fall 2021 harvest and two attacks in early 2022 that could impact the planting season by disrupting the supply of seeds and fertilizer [232].

The USDA has some mandates and resources to provide agricultural security. However, the complexity of emerging technology is creating new hazards that increase the need for interagency cooperation, which is lacking [233, 234]. In November 2022, the Biden administration released NSM-16 on strengthening the security and resilience of U.S. FA [42]. The memorandum identifies risks to the U.S. food supply system and specifically identifies cybersecurity breaches as one of the threats to the current food supply. The memorandum also stresses the need to continue to protect the United States from sophisticated malicious cyberactivity, from both nation-state actors and cybercriminals.

In addition, the "National Cybersecurity Strategy" 2023 was released by the Biden administration. The strategy seeks to protect critical infrastructures, including the FA sector, from cyberthreats. It provides guidance on defending the critical infrastructure by expanding use of minimum cybersecurity requirements in the critical sectors [235].

4.2 HISTORICAL OVERVIEW

The industry of agriculture has been around for centuries, and its history has been shaped by technological advancements. Historians have described several agriculture revolutions that identify major changes in agriculture practices and productivity that have been closely linked to technological improvements.

The 1st revolution began in the mid-17th century and represents the use of simple tools. After the steam engine was introduced in the 19th century, the 2nd revolution represented the use of machinery in production [236]. The 3rd revolution evolved through the 20th and 21st centuries and represented the use of robotics or robotization automation of processes in factories [236]. It is currently the 4th revolution of agriculture, which is referred to as "smart or digital agriculture," and it represents the use of digital technologies and is moving toward a smarter, more efficient environmentally responsible agriculture sector [236]. Figure 4-1, shows the characteristics and confronted issues of the evolution of agriculture development.

As the advancements in technologies have shaped the agriculture industry, the importance of security against cyberattacks has often been overlooked because, historically, the agricultural sector has not been a notable target for cyberattacks [231]. Recently, however, there has been an increase in cyber- and ransomware attacks within the FA sector. In 2020 and 2021, agricultural businesses of all sizes, from large corporate farms to small and midsize operations, were impacted by several major cyberattacks [237].

4.3 INTRODUCTION TO SMART FARMING

The use of modern technologies and smart devices in farming is becoming more relevant than ever and has allowed farmers to optimize their agricultural production systems while improving the economic, environmental, and manual labor outcome [238]. For example, smart farming may use several types of sensors to collect data (e.g., temperature, humidity, light, pressure, presence, etc.) and use communication networks to send and receive data, which is then managed and analyzed by management information systems and data analysis solutions [239]. This system of interconnected devices is commonly referred to as the IoT. The use of the data provided by smart farming helps boost productivity and minimize waste by allowing necessary actions to be carried out at the right time, quantity, and place [239].

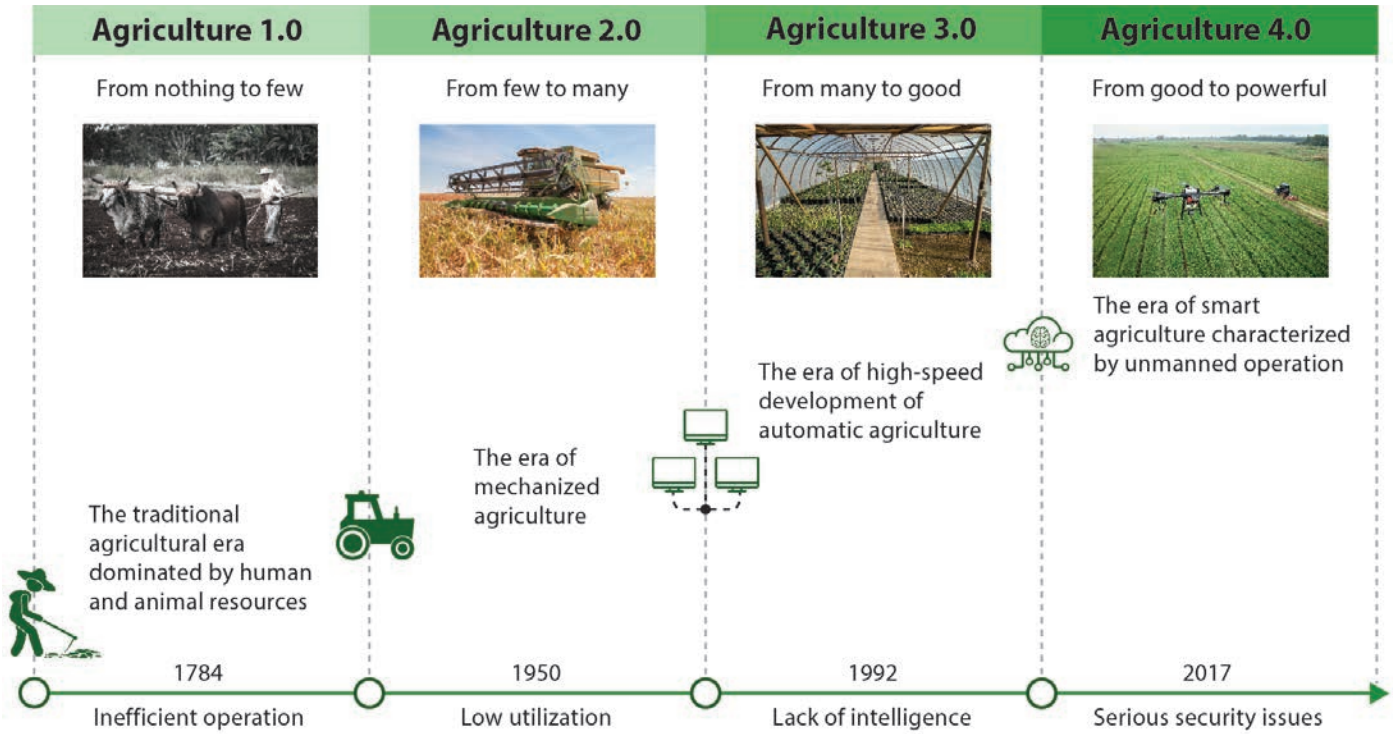

Figure 4-1. Characteristics and Confronted Issues of the Evolution of Agriculture Development *(Source: HDIAC)*.

One industry report estimates that nearly 225 million devices connected to the internet will be used in various farming and agricultural settings by 2024 [240]. Additionally, a new research report published by Polaris Market Research stated that, "The global smart agriculture market is projected to reach [U.S. dollar] USD 32.1 billion by 2030 and is expected to grow at a [compound annual growth rate] CAGR of 10.4% during the forecast period" [241].

While the introduction of smart farming technologies appears attractive for the farmers and food producers, this technological revolution has also created an environment that is increasingly conducive to cyberattacks. Through these technologies, vast amounts of data are expected to be produced, stored, and analyzed related to both a farmer and specific farm, including weather conditions, soil quality, crop growth progress, and animal health information. However, it is also because of this data that the number of potential attack surfaces has increased in agricultural settings, providing cybercriminals and nation-state actors with several potential opportunities for exploitation. For example, malicious actors could gain control of on-field sensors, make changes to data to deceive a food producer, and potentially result in the contamination of food products and the surrounding environment. Hence, cybersecurity measures and controls need to be developed, implemented, and evaluated to help reduce the risks associated with cybercrime and other cybersecurity threats to the agricultural industry [240].

Table 4-1 provides a list of key technologies used in smart farming and applications.

4.4 WHAT MAKES THE U.S. AGRICULTURE INDUSTRY AN ATTRACTIVE TARGET

Agriculture is a significant part of the U.S. economy, with millions of people employed in the industry. In 2021, the output of America's farms contributed $164.7 billion or about 0.7% of U.S. GDP [13].

Table 4-1. List of Key Technologies Used in Smart Farming and Applications

Technology	Use in Smart Farming
IoT Technologies	IoT refers to a network of interconnected items and technologies. It provides "the opportunity to combine all the tools and solutions into a single system. All devices and software can exchange data and perform specific actions based on patterns" [242].
Sensors	Sensors are used to regulate farming processes by helping farmers monitor the slightest changes in the state of the environment and fields in real time to collect data [242].
Hardware and Software Systems	"Smart farming employs hardware (IoT) and software (software as a service [SaaS]) to capture the data and give actionable insights to manage all the operations on the farm, both pre- and postharvest. The data are organized, accessible all the time, and full of every aspect of finance and field operations that can be monitored from anywhere in the world" [243].
Communicaiton Systems	Wireless communication technologies are an essential part of smart farming. Nowadays, there are several widely used communication technologies in the development of agriculture including Wi-Fi, Bluetooth, ZigBee, and LoRa [244].
Big Data Analytics	Big data refers to the information gathered where the data sets are so large and characterized by such a high volume, velocity, and variety that their traditional data-processing applications are inadequate and require specific technology and analytical methods for transformation into value [245]. The data technologies can help farmers identify trends and patterns to make better decisions.
Machine Learning	Self-learning technologies provide the power to predict changes in climate, soil and water parameters, carbon content, disease and pest spreading, and more [242]. This can help farmers make better decisions. For example, artificial intelligence can be used to predict the optimal time for planting and harvesting crops or to identify potential disease outbreaks.
Drones	Drones are used in smart farming to gather data rapidly and accurately, allowing farmers to make decisions quickly. They can be used to monitor crop health, detect pests and diseases, and collect data on soil conditions [246].
Global Positioning Systems (GPS)	GPS-based applications can be used for farm planning, field mapping, soil sampling, tractor guidance, croup scouting, variable rate application, and yield mapping [247]. GPS technology can be used to "guide and steer farming machinery and vehicles during planting, harvesting, tilling, and spraying activities, with the aim of avoiding overlapping" [240].
Cloud Computing	Cloud computing can be used to store and analyze data from IoT sensors and other sources, allowing farmers to access data from anywhere [248].
Robotics	Robotics are used in various farming operations, such as planting, harvesting, and weed control to automate manual tasks and increase efficiency [238].
User Interfaces	Smart farming systems may provide user interfaces, such as mobile apps, web dashboards, or command-line interfaces, to enable farmers and other stakeholders to monitor and control various aspects of farming operations. These interfaces can provide real-time alerts, notifications, and recommendations based on data analysis and predictive analytics [249–251].
ICTs	ICTs are used in smart agriculture to improve the efficiency of the agriculture system by connecting different devices in different layers [252]. ICT components include software, sensors, IoT devices, and data analytics.
Precision Agriculture	Precision agriculture "is a management strategy that gathers, processes and analyzes temporal, spatial, and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use, efficiency, productivity, quality, profitability, and sustainability of agricultural production" [253]. For example, farmers can use GPS technology to map their fields and apply fertilizers and pesticides only where they are needed.

Currently, there are more than 2 million farms in the United States. Family farms remain a key part in U.S. agriculture and account for 98% of all U.S. farms and 88% of total production. Most of these farms are small, family farms that only account for a small percentage of total production. Almost half of the total production comes from the large-scale, family farms, which only account for 3% of the total farms in the United States (Figure 4-2) [230].

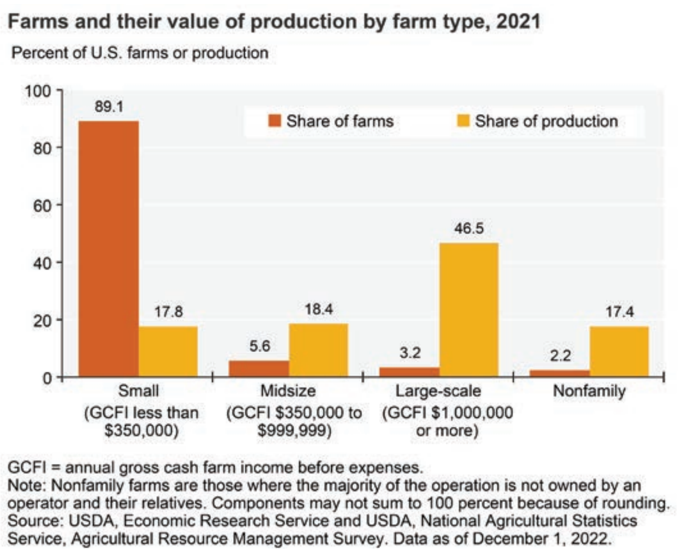

Figure 4-2. Farms and Their Value of Production by Farm Type, 2021 *(Source: Economic Research Service, U.S. Department of Agriculture [230]).*

From a cybersecurity perspective, there are several reasons why the U.S. agriculture industry is an attractive target to cybercriminals and nonstate actors. The agriculture industry is diverse and includes a wide range of targets, including farms, smallholders, food-processing companies, and agriculture equipment manufacturers. This makes it a lucrative target for cybercriminals and nonstate actors looking for a broad range of potential targets. As mentioned in Section 4.2, the agriculture industry has been shaped by technological advancements and "has not been concerned with the cybersecurity aspect of its business, but at the same time is a large contributor to U.S. exports and the overall economy from both a financial and job perspective. Further complicating matters, while the U.S. agricultural and farming industry has been designated as critical to national security, unlike other important sectors that contribute to the U.S. economy, it does not have a dedicated sector-wide agency or clearinghouse to help with cybersecurity or responses to cyberattacks" [240].

Large-scale farms are most susceptible to cybercrime, but many small farms and agriculture businesses may lack the resources and expertise to implement robust cybersecurity measures, making them a target as well. Cybercrime has become an increasing problem in the United States and agriculture sector, leading the cyberdivision of the FBI to release a notice in April 2022, alerting the FA sector that it could become a target of ransomware attacks during the busiest time of year [232]. Table 4-2 shows examples of recent cyberattacks and the impacts they have had on the agriculture sector. "Currently, [there are] no mandatory rules or standards to assist U.S. farmers secure and protect their computer systems, networks, and other machinery connected to the internet [11]. While the Biden administration has indicated that it is willing to help provide steps for farmers to harden their information technology infrastructure, at the time of writing, minimal guidelines had been published to assist with this effort" [240].

4.5 SECURITY CHALLENGES IN SMART FARMING

In a smart farming system, data is processed in real or near-real time to aid farmers in making highly informed decisions on how to manage their crops [254]. Large amounts of data are generated that are extremely valuable to farmers and other people, including bad actors. If a bad actor were to corrupt the data involved in smart farming, it could lead to a large downstream impact on inputs (e.g., water, fertilizer) and, therefore, the cost of food production [254].

Table 4-2. Examples of Recent Ransomware and Cyberattacks That Impacted the FA Sector

Year	Attack	Impact
2020	In November 2020, a U.S.-based international FA business reported it was unable to access multiple computer systems tied to its network due to a ransomware attack conducted by OnePercent Group threat actors using a phishing email with a malicious zip file attachment. The cybercriminals downloaded several terabytes of data through the identified cloud service provider prior to the encryption of hundreds of folders [232].	The company's administrative systems were impacted. It did not pay the $40-million ransom and was able to successfully restore its systems from backups [232].
2021	A ransomware attack against a U.S. farm resulted in losses of approximately $9 million due to the temporary shutdown of its farming operations [232].	The unidentified threat actor was able to target its internal servers by gaining administrator-level access through compromised credentials [232].
2021	A malware attack at a water treatment facility in Florida allowed hackers to use remote-access software to raise the levels of sodium hydroxide in the water from about 100 parts per million to 11,100 parts per million for a few minutes. This attack occurred about 15 miles from the location of the treatment facility and 2 days before the Super Bowl [255].	Fortunately, an employee noticed the attempt as it was occurring, and stopped it. However, if successful, the attack would have increased the amount of sodium hydroxide to an incredibly dangerous level in the water supply [255].
2021	One of the most famous ransomware attacks against the FA sector was against JBS, the largest supplier of meat in the world. On 30 May 2021, JBS experienced a cyberattack that temporarily shut down its facilities in the United States, Canada, and Australia [256]. The FBI says that Ransomware Evil (also known as REvil or Sodinokibi), a Russian-speaking ransomware gang, was likely responsible for the cyberattack against JBS [257].	Chief Executive Officer Andre Nogueria made the difficult decision to pay the ransom of $11 million to prevent any potential risk of its customers [257].
2021	A ransomware attack to a U.S. baking company caused it to lose access to its server, files, and applications, which resulted in having to halt production, shipping, and receiving. It was deployed through software used by an internet-support-managed service provider [237].	The baking company was shut down for approximately 1 week, delaying customer orders and damaging the company's reputation [237].

A cyberattack on a smart farming system can result in data theft, system downtime, and financial losses. Smart farming collects a large amount of data, including sensitive information about crops, weather patterns, and even farm operations. If not adequately protected, these data can be compromised, leading to privacy breaches and potential misuse. Hackers can exploit vulnerabilities in software or hardware, access sensitive data, or even take control of automated farming equipment. Additionally, since most of the machinery used in smart farming is reliant on cloud-based storage and connected online, it introduces several vulnerabilities to physical attacks on data centers or communication networks that would have disastrous consequences [254].

For smart farming to be a success, farmers need to abandon traditional mechanical labor-intensive practices and place their farms online, embracing technologies such as mobile devices, cloud computing, and wireless networks. It is through the adoption of these technologies that many farmers are now vulnerable to the potential exploitation of cybervulnerabilities, which exist within these technologies. While many of these technologies have been embraced by other critical industries (e.g., finance and healthcare) and the cybersecurity risks have been both understood and (largely) mitigated, this does not appear to be the case within the *farming and agricultural domain. There could be several reasons for this. The first reason is that many farmers and agricultural providers could have limited investment in cybersecurity defenses simply because they do not see cybersecurity as a "big enough" problem. Hence, issues such as floods, fires, hail, and even insect problems could register higher up when it comes to the risks they might face when attempting to maximize crop yields, while minimizing costs. Support for this theory is supported by a DHS report that surveyed several large farms, and smart farming technology manufacturers throughout the United States and found that many individuals did not fully understand the cyberthreats introduced by smart farming, nor did they take these cyber-risks seriously enough. This leads to the second reason, limited oversight, and regulation at a governmental level. In 2010, two U.S. federal government agencies (the USDA and the FDA), both classified cybersecurity as a low priority. While this was reversed in 2015, the damage was already potentially done. While other industries classified as critical infrastructure (e.g., financial services) developed and published numerous countermeasures, best practices, and legislation guided toward cybersecurity, the same cannot be said for the agricultural sector [240].*

4.5.1 Cybersecurity Vulnerabilities

"At the heart of cybersecurity is the CIA triad of confidentiality, integrity, and availability" [240]. Authentication and nonrepudiation were added because they are also important concerns to information security.

The National Institute of Standards and Technology Computer Security Resource Center defines a cyberattack as "any kind of malicious activity that attempts to collect, disrupt, deny, degrade, or destroy information system resources or the information itself" [258]. The outcome of a cyberattack to a smart farming system would be similar to other systems that could threaten any one of these elements.

Next are definitions and examples on how a cyberattack can threaten the confidentiality, integrity, availability, authentication, and nonrepudiation of a system.

Confidentiality. Confidentiality is defined as "preserving authorized restrictions on access and disclosure, including means for protecting personal privacy and proprietary information" [259]. Data confidentiality makes sure that the farmers yield data, farming methods, and other proprietary information are protected against unauthorized access. A common threat to confidentiality is data theft.

The theft of IP can cause significant harm to a company. Acquiring U.S. trade secrets through agricultural espionage could allow a foreign nonstate actor to improve their agricultural output and become more competitive in global markets.

Integrity. Integrity is defined as "guarding against improper information modification or destruction and ensuring information nonrepudiation and authenticity" [259]. Data integrity ensures that the information is not altered during storage or transmission. An attack on the integrity of a smart farming system can result in the manipulation, alteration, or deletion of critical data.

Intentional falsification of data could disrupt crop or livestock sectors. "This is the highest impact threat identified under integrity standard and the highest impact threat identified overall. It is an easy threat to potentially manifest, as it does not rely on original access to real data" [260].

A malicious actor could inject false data into a sensor network, which is often connected via cellular, Bluetooth, or wireless networks. The injection of false data can "result in issues like underwatering of a crop, destroying it" [260]. Additionally, a malicious actor can release data regarding a disease outbreak that could ruin public confidence in that industry, driving prices down too low for farmers to sustain.

Availability. Availability is defined as "ensuring timely and reliable access to and use of information" [259]. Sensors, devices, and equipment generate an enormous amount of complex, dynamic, and spatial data [261]. Data availability ensures the continuity of provided services to genuine users [229, 262]. An attack on the availability of a smart farming system can result in system downtime, making it impossible for farmers to access critical information and perform necessary tasks that can lead to decreased productivity, loss of revenue, and even crop failure.

Autonomous irrigation systems that use sensors to measure crop moisture levels in real time are vulnerable to cyberattacks such as a deauthentication attack [263]. This type of attack would prevent the irrigation system's decision-making because the sensors would be blocked from connecting to the network obstructing real-time communication [263]. If this type of attack happened during a heat wave, which is increasing more frequent, as discussed in Section 2 of this report, or at a specific time, such as planting or harvesting, it would have the potential to destroy an entire season worth of crops [264].

Authentication. Authentication is defined as "verifying the identity of a user, process, or device, often as a prerequisite to allowing access to a system's resources" [265]. One of the most important aspects of security and privacy in smart farming is authentication of connected devices. Before devices (i.e., sensors, drones, etc.) connect the services, it is important that they are authenticated [261].

Data authentication also guarantees that only authorized and authentic users have access to the data, making it impossible for a user to spoof another identity [229, 262].

Nonrepudiation. Nonrepudiation is defined as "assurance that the sender of information is provided with proof of delivery and the recipient is provided with proof of the sender's identity, so neither can later deny having processed the information" [266]. Nonrepudiation prevents users from denying (repudiating) what they have done in the system. An attack on the nonrepudiation of a smart farming system can result in the inability to prove the authenticity of data or transactions, making it challenging to detect fraudulent activity. "This requires unique identifiers and tagging/auditing of transactions with that unique identification so that one cannot deny initiating that transaction. For example, an email signed with my [common access card] CAC had to come from me and nobody else because who else would have access to my CAC and know my PIN" [267].

Without the proper provisions for security aspects previously discussed, the use of smart farming "may be exposed to a variety of attacks that may exploit these environments and related smart information systems or cause harm, stealth, unauthorized change, or destruction on them" [229].

4.5.2 How to Target Agriculture Industry

A typical multilayer smart farming architecture technology is like any other IoT system and is made up of multiple layers of data collection, processing, handling, and storage that are susceptible to data loss. The layers are referred to as the perception layer, the network layer, the edge layer, and the cloud layer. Figure 4-3 shows the structure of a smart farm and the components found in each layer [268].

- The perception layer, also referred to as the end-device layer, relates to the physical

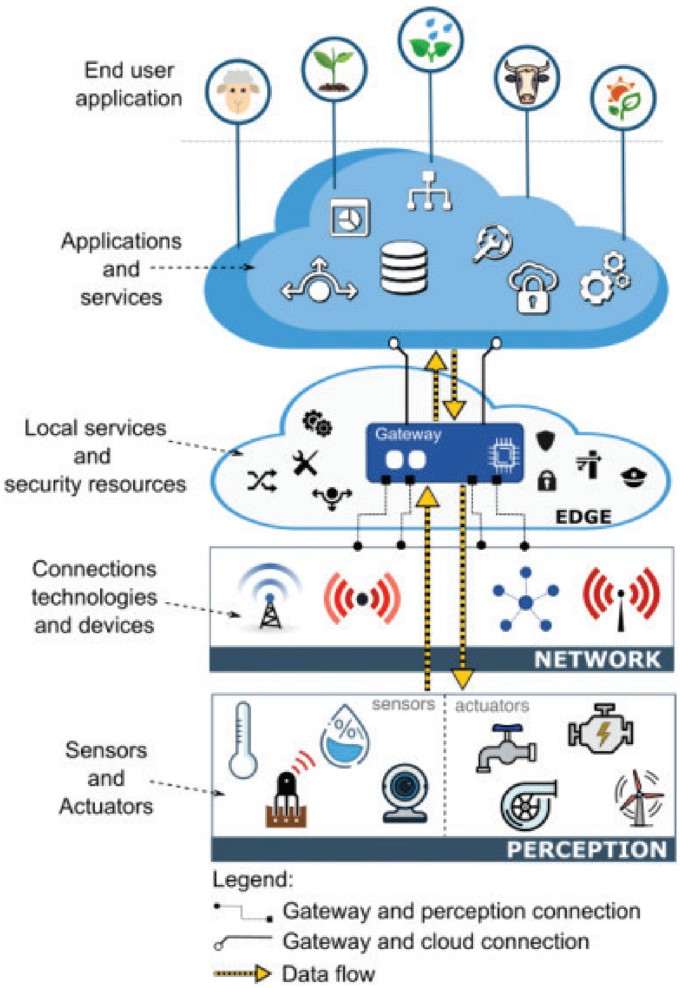

Figure 4-3. Structure of Multilayer Smart Farming *(Source: Zamella et al. [268])*.

devices such as sensors, actuators, GPS, radio-frequency (RF) identification tags, and other devices that are used to collect both field environment and crop growth information [269]. These devices are not capable of processing or storing data and are connected to a gateway that is linked to a local computer through the network layer.

- The network layer consists of connection technologies and devices, usually a wireless sensor network, and is used to transfer data. The information from the perception layer is uploaded to a higher layer through the network layer for further processing and analysis [270].
- The edge layer consists of multiple edge nodes. Each node represents a gateway that includes a variety of resources such as security features, data filtering, software features applied to decision-making and data processing, and storing small amounts of data [261].
- The application layer, which is located in the cloud, consists of all applications that are used by the end user. It includes the database systems where the data produced by the smart system are stored and decision-making happens [268].

By incorporating the use of smart communication technologies, as well as the integration of IoT, several security threats and vulnerabilities in smart farming are introduced that are mostly related to cybersecurity, which is discussed in Section 4.5.3 [254].

4.5.3 Types of Cyberattacks and Weaknesses to Smart Farming Systems

Each layer of a smart farm system is vulnerable to different types of attacks and weaknesses. Table 4-3 shows the vulnerabilities to each layer in a multilayered smart farming system and the most common type of cyberattacks to happen in each layer.

There are different types of attacks that can be executed by attackers. These types of attacks can be categorized into data attacks, networking and equipment attacks, hardware attacks, supply chain attacks, code attacks, and misuse attacks, as can be seen in Figure 4-4. Examples for each category include:

- Hardware Attacks
  - Side Channel: A side-channel attack is a type of cyberattack that targets the information leaked by a system's physical components to extract sensitive information [271].

Table 4-3. Vulnerabilities to the Layers in a Multilayered Smart Farming System and the Most Common Type of Cyberattack in Each Layer

Layer	Threat	Most Common Type of Cyberattack
Perception/ End-Device Layer	• Threats to the perception/end-device layer "are related to hardware, physical access, damage, firmware/hardware modification, or the wrong actuation to destroy crops" [271]. • "Fitting GPS technologies together with [controller area network] CAN bus systems into machinery and vehicles allows an attacker to potentially exploit known vulnerabilities with these technologies. This could allow an attacker to gain control of the vehicle/machinery, which could then be used to launch further physical attacks. Similarly, cybercriminals and malicious actors could look to exploit sensors connected to irrigation and watering systems. Exploiting such technology on a mass scale could allow attackers to waste valuable water resources, which could be especially problematic in drought-affected areas" [240].	Misconfiguration, Side-Channel Attacks, Third-Party Attacks, Data Fabrication, and Software Update Attacks
Network Layer	• Threats to the network layer "are related to data in transit and involve network devices and communication protocols. Vulnerabilities can be exploited to sniff out and access data, leading to diverse attacks" [271]. • "Associated technologies that are used in this layer include Zigbee and the IEEE 802.11 protocol. Attacks that are possible in this layer include password cracking (exploiting vulnerabilities in wireless networks to later 'sniff' information), evil access point (tricking a farmer or system to connect to the access point for the purpose of collecting information), address resolution protocol attack (attacker fakes the MAC address of a gateway and smart devices, and systems interact with this malicious gateway), and domain name system attacks (allowing an attacker to intercept network traffic between the client and the gateway)" [240].	Denial of Service (DoS), Routing, Jamming, Man in the Middle (MiTM), and False Data Injection
Edge Layer	• Threats to the edge layer "are related to data at rest, either in the cloud or on premises. The compromise of data could lead to IP theft" [271]. • "Cybersecurity concerns in this layer surround the introduction of rouge and malicious data that could result in either over- or underwatering of crops, under- or overutilization of fertilizer, and even the disruption of [heating, ventilation, and air-conditioning] HVAC systems in automated chicken coops, potentially destroying entire broods in a single barn" [240].	Malware, Cloud Data Leakage, Botnets, and Cloud-Computing Attacks
Application Layer	• Threats to the application layer related to "the compromise of credentials through social engineering or malware injection could compromise the whole system" [271]. • "Threats and concerns regarding these technologies include MiTM attacks of smartphone applications, allowing the interception of farming data, DoS attacks, session hijacking and traffic flow analysis, data leakage from both data rest and data in motion, as well as successful ransomware attacks due to limited backup practices" [240].	Phishing, Data Leakage, Ransomware, Cyberterrorism, Indirection Attack, Buffer Overflow, Invalidation, and Compliance

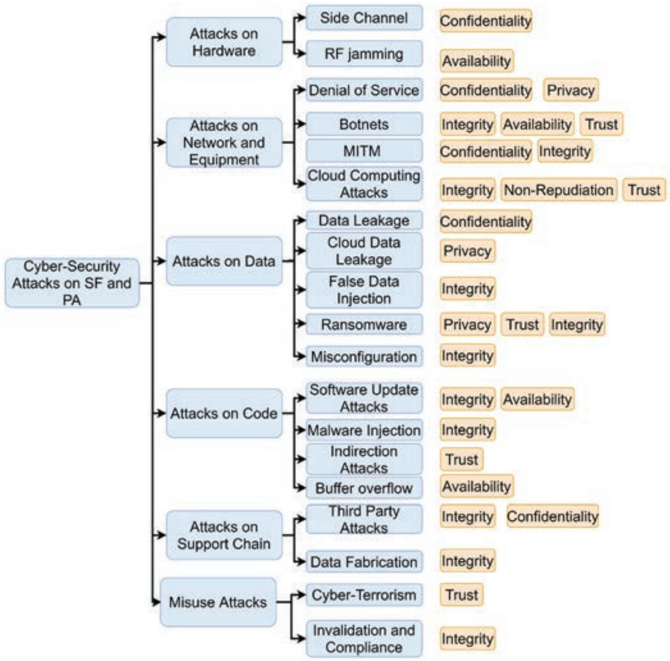

Figure 4-4. Cyberattacks on Smart Fishing Systems and Their Threat to Cybersecurity *(Source: Yazdinejad et al. [229]).*

- RF Jamming: RF jamming attacks "are caused by the open nature of wireless channels and the progress in designing jamming-resistant wireless networking systems. Attacks of this type violate the availability of the systems in the smart farming and precision agriculture area like a greenhouse" [229].

- Networking and Equipment Attacks
  - DoS: A DoS attack shuts down a machine or network by overwhelming the system with traffic, requests, or commands. This prevents users or devices from their authorized access [229]. A DoS attack to a smart farming system could "prevent measurements from reaching the edge or cloud on time, delay commands to actuators, and make services unavailable" [269].
  - Botnets: A botnet attack is where a network of malware-infected devices (zombie bots) that are controlled remotely by a threat actor. Botnet attacks pose a great threat because they can deploy large-scale attacks at the same time and the threat actor is usually working within the network, unlike malware attacks that replicate themselves within a single machine or system [272].
  - MiTM: An MiTM attack is when data that are transmitted over a connection are stored and replayed [229]. This allows access to communication between nodes. An MiTM attack could result in the loss of personal information, such as login credentials.
  - Cloud-Computing Attacks: Cloud-computing attacks "misuse cloud features such as self-provisioning, on-demand services, and autoscaling to take advantage of cloud resources. For instance, an infected virtual machine can quickly spread the infecting malware to other virtual machines via the cloud" [229].

- Data Attacks
  - Data Leakage: Data leakage is the unauthorized transmission of data from an organization to any external source [229].
  - Cloud Data Leakage: Cloud data leakage "is the exposure of data related to the users of an organization or the provided services, which violates the privacy of users or parties" [229].
  - False Data Injection: False data injection "feeds intentional falsification of data into the sensor network, which is connected via Wi-Fi/Bluetooth/cellular and can result in over/underwatering of crops" [273].
  - Ransomware: A ransomware attack is a type of malware that is designed to encrypt files on the organization's network, make the files or system unusable, and demand a ransom to receive the encryption key [229].
  - Misconfiguration: Misconfiguration "is the action of configuring the smart farming or precision agriculture reporting systems

in a way that reflects invalid information regarding the managed farm, which can lead to costly, disruptive decisions and actions from the farmers. Misconfiguration attacks violate the integrity" [229].

- Code Attacks
  - Software Update Attacks: Software update attacks "violate the integrity and the availability of the system via disrupting the update process of the installed software" [229].
  - Malware Injection: A malware injection is when the cyberattacker creates a malicious application and injects it into the SaaS, platform as a service, and the infrastructure as a service, respectively [274]. An example could be from a phishing attack when an attacker attempts to trick a user into doing the wrong thing, such as clicking a bad link in an email, which will download malware, or directing users to a dodgy website.
  - Indirection Attacks: Indirection attacks "use code-injection techniques to mislead the database server to run malicious structured query language codes injected into entry fields of the database. Indirect attacks violate trust" [229].
  - Buffer Overflow: Buffer overflow "is a software coding error or vulnerability that hackers can exploit to gain unauthorized access to corporate systems. This kind of attack violates availability" [229].
- Supply Chain Attacks
  - Third-Party Attacks: Third-party attacks "occur when an adversary infiltrates a system via an outside partner or provider who has access to the system and/or the data. Third-party attacks can violate the confidentiality or the integrity of the system" [229].
  - Data Fabrication: Data fabrication "involves the creation of malicious data or processes misusing an access provided for another purpose. It can lead to the violation of the system's integrity" [229].
- Misuse Attacks
  - Cyberterrorism: Cyberterrorism "may use IoT systems and cyberphysical devices to attack people or premises from afar. This can lead to the violation of trust in smart farming and precision agriculture systems" [229].
  - Invalidation and Compliance: Invalidation and compliance "refers to disruptions in the certification process created by fabricated false data. These attacks target the integrity of the system" [229].

4.5.4 Defense Applications

According to Dan Coats, former Director of National Intelligence, "Frankly, the United States is under attack—under attack by entities that are using cyber to penetrate virtually every major action that takes place in the United States. From U.S. businesses, to the federal government, to state and local governments, the United States is threatened by cyberattacks every day" [275].

Adversaries target U.S. IP aggressively. "China's efforts to gain access to data on U.S. GM grains present serious concerns for U.S. economic competitiveness as Chinese firms illicitly acquire U.S. IP." China has employed innumerable methods to obtain U.S. IP, including cyberattacks. "Acquiring U.S. trade secrets through agricultural espionage has become a convenient way for China to improve its agricultural output and become more competitive in global markets." For example, a foreign national employed by the U.S. company Monsanto "stole a valuable algorithm used in online farming software to help farmers collect, store, and visualize field data" [276].

In an interview, with the House Appropriations Subcommittee, FBI Director Christopher Wray asserted that China has "a bigger hacking program than that of every other major nation combined" and that "it affects everything from agriculture, to aviation, to high-tech, to healthcare" [277]. To that end, "Agricultural genetic technologies present unique dual-use potential that may attract further economic espionage" [276].

There have been multiple cases of foreign nationals from competitor nations stealing IP across all sectors of the economy. Sometimes, this is via physical means. Specific to the agricultural sector, people have stopped trying to smuggle samples, seeds, and even whole plants out of the country. Cybercrime is considered the lower risk method and can be undertaken from outside of the target nation's borders. The threat may also emerge from inside the border of the target nation. In 2021, an indictment was returned against four Chinese citizens for "targeting trade secrets, IP, and other high-value information from companies, universities, research institutes, and governmental entities" [278].

The United States tends not to think of food production and agricultural security when it comes to national security strategizing, but other nations absolutely do. This has created an imbalance where the desire to attack the agriculture sector's information systems is far greater than the willingness to defend it. The defensive capabilities of the agricultural sector's cybertechnology are as varied as the entities that operate it, from large corporations providing feed, seed, fertilizer, and operating farms down to individual farmers and everything in between.

4.6 CONCLUSION

According to the Internet Security Alliance "Cyberterrorism is a relatively low-cost venture with high payoff potential" [279]. The low cost of deploying a cyberattack is mostly limited to the skills or imagination of the attacker compared to the cost of repairing the damage, which is huge. In 2018, Deloitte released a threat study titled, "Black Market Ecosystem: Estimating the Cost of Ownership," which estimates that some "common criminal businesses can be operated for as little as $34 month and could return $25,000, while others may routinely require nearly $3,800 a month and could return up to $1 million" [280].

With a move into a more digital world, the increase of risks to cyberattacks is increasing exponentially. In 2021, the FBI released its annual Internet Crime Complaint Center report, which shows a record number of 847,376 complaints from the American public, with potential losses exceeding $6.9 billion. This is a 7% increase from the number of 791,790 complaints recorded in 2020 [281]. As the agriculture industry adopts the use of smart technology, it is important that it also assesses the risks of cybersecurity attacks and puts appropriate security measures in place. The FA sector is already being impacted by climate change; imagine the effect that a cyberattack could have on one of the large-scale farms during a heat wave. A third of the U.S. production of crops could be lost, causing detrimental impacts to the food supply chain.

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SECTION 05 CONCLUSION

The FA sector is one of the sixteen sectors of critical infrastructure listed by the Cybersecurity and Infrastructure Security Agency [12]. It is the largest and most essential sector for human life. It is also the most vulnerable to various threats from climate change, biological outbreaks, and cyberattacks. These threats can disrupt the FA sector in many ways, such as:

- Climate change can alter the environmental conditions that influence the FA sector, such as temperature, precipitation, water availability, soil quality, pest and disease dynamics, and crop yields. These changes can lower the productivity and profitability of the FA sector, as well as increase the risk of food insecurity, malnutrition, and conflicts.
- Biological outbreaks can cause diseases in crops, livestock, and humans that can reduce the quantity and quality of food production and pose health risks to consumers and workers. Biological outbreaks can also disrupt the supply chains and trade of food products, as well as trigger social and economic impacts. Biological outbreaks can also be used as a weapon of agroterrorism to modify genes or deliver a biological agent across a large area.
- Cyberattacks can target the information systems, networks, devices, and infrastructure that support food production, processing, distribution, and consumption. These attacks can compromise the data integrity, confidentiality, and availability of the FA sector, as well as cause physical damage, operational disruption, financial losses, and reputational harm.

The challenge is how to increase the food supply for the growing population without increasing GHG emissions while keeping the food supply safe from these threats. The global population is projected to reach 9.7 billion by 2050, which will increase the demand for food by 50% [9]. The FA sector relies heavily on technology and innovation to meet the growing demand for food. It uses technology such as sensors, unmanned systems, software, and the internet to monitor and improve plant and animal health, soil conditions, weather, accounting, communication, tracking, forecasting, and buying and selling goods and equipment. However, each use of technology is also a potential gap that must be protected from physical and cyberthreats.

The FA sector faces multiple and diverse adversaries who have motives to target it. These include terrorist groups, state-sponsored actors, lone wolfs, and even industry competitors. The FA sector is challenging to protect because of its size and scope. It includes large, corporate farms, as well as small, family farms. Every farmer is a potential target of these adversaries. While a large farm would be an attractive target, hacking into a small farm's sensor network to indicate a disease outbreak could have a domino effect on the surrounding area.

It is important to assess these threats to the FA sector as a collective challenge and not each threat separately. As previously mentioned, half of food production comes from 3% of large-scale, family farms, and corn accounts for a quarter of U.S. crop commodities that are exported. The United States is also the largest exporter of beef and poultry. Being one of the critical infrastructures, it is key that the threats are assessed and proper policies/actions are put into place before an outbreak or cyberattack happens or else the outcome would be catastrophic to U.S. national security and the economy. The threats to the FA sector are interrelated and impact on each other. For example:

- Climate change can increase the likelihood and severity of biological outbreaks by altering the distribution and transmission of pathogens and vectors.
- Biological outbreaks can increase the vulnerability of the FA sector to cyberattacks by creating opportunities for malicious actors to exploit weaknesses in information systems or infrastructure.
- Cyberattacks can exacerbate the impacts of climate change or biological outbreaks by disrupting the mitigation or adaptation measures or by spreading misinformation or panic.

The FA sector is critical for both domestic and international security. The domestic food supply is the military food supply. The DoD has a vested interest in monitoring and protecting the food supply. International interruptions may impact the U.S. food supply or form the basis of instability and eventual need for U.S. intervention. At best, a regional shortage would impact international prices and availability. At worst, it could lead to famine and conflict.

Protecting the FA sector requires a whole-of-government approach. The DoD may play a supporting role in many cases, but the consequence of inaction may be as grave as any other enemy action.

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AGRICULTURAL SECURITY: IMPACTS ON MILITARY READINESS AND NATIONAL SECURITY

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