Emerging climate change issues

Scientists are reporting changes in California's environment that are plausibly — but not yet established to be — influenced by climate change. The link to climate change is supported by scientifically defensible hypotheses, models, and/or limited data. However, deciphering the influence of climate among other factors presents a challenge. Factors such as land use and environmental pollution, as well as the inherent variability of the climate system, make it difficult to attribute some of these changes and impacts to climate change. Environmental changes and trends for which the influence of climate change remains uncertain are discussed in this section as ***emerging issues***. Additional data or further analyses are needed to determine the extent by which climate change plays a role.

Changes in Climate

Central Valley Fog

Fog, which is a cloud (stratus or stratocumulus) at or near the ground or ocean surface, consists of droplets 100 times smaller than raindrops that stay suspended in air, sometimes coalescing into drizzle or collecting on surfaces to form "fog drip" (AMS, 2022). Valley fog promotes colder temperatures during the winter, a critical factor for achieving a period of dormancy ("winter chill") in agricultural regions such as the Central Valley. Both anecdotal evidence and field measurements indicate that California's Central Valley winters are less foggy than they were several decades ago. In one study, scientists collected data from satellite imagery and weather stations to analyze weather conditions and occurrences, spatial extent and long-term trends in "tule fog" — a thick winter ground fog that blankets the valley (Baldocchi and Waller, 2014). The researchers paired satellite records from the National Aeronautics and Space Administration and the National Oceanic and Atmospheric Administration with data from a network of valley weather stations and counted the number of days each year when fog occurred during the winter from 1981-2014. Over the 33-year timespan, the number of winter fog events decreased 46 percent, on average, with much year-to-year variability. The optimal meteorology for Central Valley fog formation occurs during winters with periodic storms followed by periods of high pressure across California. This allows ample humidity from evaporating soil moisture to condense and form fog during the cold, clear nights (Baldocchi and Waller, 2014).

Rising temperatures in densely populated areas (the "urban heat island effect") have been associated with a decline in the number of days and spatial extent of valley fog (Klemm and Neng-Huei, 2016). Increasing temperatures make it more difficult for atmospheric water vapor to condense and less likely for fog to form. Further, higher temperatures can evaporate fog that forms (hence, fog evaporates in the morning when the sun rises). In addition to air temperature, drought years tend to be associated with lower numbers of fog days because there is not enough evaporating soil moisture to form fog (Baldocchi and Waller, 2014).

Other studies report that the observed reduction in fog in the Central Valley and in other areas worldwide correlates more with a decline in air pollution (Gray et al., 2019; Gray et al., 2016; Klemm and Neng-Huei, 2016). Airborne particles, including dust and other air pollutants, serve as nuclei for water vapor to condense around. One study concluded that climate variables (in particular, the difference between ambient temperatures and dew point) strongly influenced the short-term, year-to-year variability in fog frequency; however, changes in air pollution are driving long-term temporal and spatial trends in Central Valley fog (Gray et al., 2019). This study found that from 1930 to 1970, valley fog significantly increased due to high levels of nitrogen oxide emissions attributed to a surge in use of motor vehicles. The downward trend in fog frequency since 1980 is consistent with the trend of decreasing air pollution due to statewide vehicular emissions regulations over the past decades. While decreasing air pollution appears to be a major factor in the decline of fog formation, scientists recognize that rising temperatures also play a role and will likely have a significant impact as temperatures continue to rise in the future. The concurrent roles of changes in air pollution (including agricultural burning) and climate on changing fog trends in the Central Valley remain an area of ongoing research.

Coastal Fog

Coastal marine fog is an important climatological feature of California (USGS, 2022). It is formed by complex interactions involving ocean evaporation, aerosols, atmospheric pressure, vertical air layering, onshore-offshore temperature gradients, and coastal mountain topography. In hilly terrain along the California coast, the low cloud layer touches the ground at higher elevations. Coastal fog is a result of a delicate balance between moist marine air cooled by the ocean and an upper layer of drier, warmer air capping the fog layer, forming an inversion. As it moves from the ocean into coastal California, marine fog provides moisture to the arid and semi-arid coast, especially in the warm summer months.

Globally, observations of fog from ships since 1800 are available, as well as observations from airports since 1950, and from satellites since 1980. Each of these vantage points gives a different perspective on long-term trends. Off the California coast, ship-based observations show an increasing trend in summertime marine fog (that is, fog over the ocean) since 1950 (Dorman, 2017). Over land, a study found a 33 percent reduction in summertime coastal fog frequencies along California’s coastal redwood region from 1951 to 2008 (Johnstone and Dawson, 2010). Reductions in summertime coastal fog due to shifts in coupled ocean-atmospheric processes have also been observed globally, including Hokkaido, Japan (Sugimoto et al., 2013); the Kiril Islands, Russia (Zhang et al., 2015); and in Europe (Egli et al., 2017).

Coastal fog formation is driven by many climate processes and physical influences (Clemesha et al., 2017; Koračin et al., 2014). High pressure zones over the Pacific, which help to produce inversions, can change position leading to changes in fog frequency. Strong coastal winds can increase colder ocean water upwelling, leading to a thicker fog layer (Dorman, 2017). Turbulence between layers of moist air and dry air can carry moisture out of the fog layer as it mixes into the drier air layer above it, dissipating the fog. In addition, highly localized offshore and onshore movements of fog are affected by complex topographical features such as mountains and other geological barriers (Torregrosa et al., 2016; Wang and Ullrich, 2017).

Warming temperatures can have a strong influence on some of the processes affecting fog formation. Periodic increases of coastal fog have been associated with the warm phase of the Pacific Decadal Oscillation, an ocean temperature index (Witiw and LaDochy, 2015). Changes in global air patterns can also cause strong changes in fog at the local level. For example, the resilient atmospheric ridge that parked warm dry air over California in August 2017 shut down the usual pattern of onshore coastal fog advection into coastal ecosystems (see also September 2010 event, Kaplan et al., 2017). How these climate processes work together under the influence of changing climate conditions is not well understood.

In addition to large-scale climate forces, fog formation is influenced by local conditions. Studies of coastal fog in Southern California report reductions in fog near densely populated urban areas (LaDochy and Witiw, 2012; Williams et al., 2015). Urban surfaces warm during the day, causing warmer nighttime air temperatures that prevent fog droplets from forming. Declining atmospheric particulate levels are also associated with reductions in coastal fog in Southern California.

Fog plays a vital role in coastal ecosystems. Species restricted to the coastal zone such as coastal redwood trees can get up to a third of their water from fog (Burgess and Dawson, 2004). Plants in fog-filled forests can take in water through their leaves, supplying lifesaving “fog drip” to salmon and trout in low flow coastal streams that would otherwise dry out during the late summer dry season (Dawson, 1998; Sawaske and Freyberg, 2015). Shade from summertime fog and low clouds cool coastal systems, reducing the rate of plant evapotranspiration and plant uptake of subsurface water reserves, leaving more water in the system (Chung et al., 2017). Summertime fog and low clouds carried by winds move deep into California’s northwestern oriented valleys that are some of the states’ most productive agricultural regions, including the Salinas Valley and the wine grape growing regions of Sonoma and Napa counties (Torregrosa et al., 2016). Crop irrigation demand has been shown to decrease during fog events (Baguskasa, 2018).

The disappearance of fog in late summer can exacerbate the climatic water deficit for entire watersheds, leading to fire-ready tinder conditions. In urban areas, the disappearance of summertime fog leads to warmer summertime temperatures that result in greater electrical demand for cooling. Coastal fog and cloud cover can also play a role in a watershed's capacity to provide cool water to streams that serve as habitat for Coho salmon and other salmonids (Torregrosa, et al., 2020). The importance of fog to California's water and energy balance and to human and ecosystem wellbeing is receiving increased attention and study (Burns, 2017; McLaughlin et al., 2017; Torregrosa et al., 2014). Research on climate change impacts on fog formation will help to improve forecasts of future trends and understanding of coastal fog impacts on California. Researchers are even exploring the use of geoengineering to increase marine clouds to cool the planet (Ahlm et al., 2017).

Lightning

Lightning is a transient, high-current electric discharge in the atmosphere. Air movements and collisions between particles of liquid water, ice crystals and hail in clouds cause these particles to become charged. Air acts as an insulator between the positive and negative charges in the cloud and between the cloud and the ground. When the opposite charges build up above a certain threshold, the insulating capacity of air breaks down, resulting in a rapid discharge of electricity known as lightning. The flash of lightning temporarily equalizes the charged regions in the atmosphere until the opposite charges build up again (NSSL, 2018, Schumann and Huntrieser, 2007).


Source: NASA

A number of studies have shown that lightning activity is sensitive to surface air temperature changes (Price, 2013). An analysis of observational data for the contiguous United States found precipitation and convective available potential energy (CAPE), a measure of atmospheric instability, to be highly correlated with lightning frequency (Romps et al., 2014). Using climate models that predict an increase in CAPE and variable changes in precipitation over the 21st century, the researchers estimated an increase in annual mean lightning strike frequency of 12 percent per degree Celsius (°C) increase in global average temperature (an increase of about 50 percent over this century, based on a projected 3.6°C increase in temperature). However, other studies that account for the effect of warming temperatures on the formation of ice particles in clouds projected decreases in lightning activity globally (Finney, et al., 2018; Jacobson and Street, 2009). Aerosols from industrial processes and transportation services may also impact lightning; during the COVID-19 lockdown period, lightning strikes decreased drastically in Europe and

Oceania compared to the previous year due to reduced human activity and significant reduction in particulate matter and aerosol concentrations (Yusfiandika, et al., 2021).

A review of studies on the effect of climate change on lightning found inconsistent projections, and concluded that the widely different results indicate a need to better understand the dynamics and life-cycle of thunderstorms in different geographical and seasonal settings (Yair, 2018; Holzworth et al., 2021). These conflicting findings suggest the need for further research, particularly in light of the role that lightning plays in initiating wildfires.

Lightning can amplify climate-related impacts by igniting wildfires and producing atmospheric greenhouse gases. Lightning-initiated wildfires have driven most of the recent increase in large wildfires in the forests of western United States, including California (NIFC, 2022; Li, et al., 2020). Lightning produces nitrogen oxides that lead to the production of tropospheric ozone, a potent greenhouse gas (Schumann and Huntrieser, 2007).

Vegetation and Wildlife

Cyanobacterial Harmful Algal Blooms (Freshwater)

Cyanobacterial harmful algal blooms (CyanoHABs) are colonies of plant-like bacteria that grow out of control and often produce toxins (cyanotoxins), threatening inland water ecosystems, public health, and economies. In California, CyanoHABs mainly occur in freshwater and low salinity waterbodies. Globally, they are expanding in occurrence, distribution, intensity, and toxicity due to a combination of climate change and anthropogenic eutrophication (the overabundance of nutrients in a waterbody due to the actions of people) (Ho et al. 2019; Paerl and Barnard, 2020; Taranu et al. 2015,). In California, CyanoHABs have been increasing over the past 40 years based on periodic and anecdotal data (SWRCB, 2021). Ongoing observational data between 2016 and 2020 also show that CyanoHABs are increasing spatially and temporally throughout the state, occurring in freshwater bodies from high elevation to the coast and sometimes lasting from 6 to 12 months. In 2020, California received 370 reports of CyanoHABs compared with 190 reports in 2018. Reporting is voluntary so this is likely an undercount of CyanoHABs for the state.

Climate change drivers of CyanoHABs include increasing water temperatures, changing precipitation rates, rising occurrences of extreme storm events, and increasing carbon dioxide levels (Paerl 2016; Paerl and Paul 2012; Paerl et al. 2018). Increasing temperatures cause CyanoHABs to grow faster, to appear in places that were previously unsuitable to them and to appear at new times of the year and for longer durations (Suikkanen et al., 2013). Increasing temperatures also result in water stratification, which provides an excellent setting for CyanoHABs. Increased precipitation significantly increases the transport of nutrients from land to surface waters, which promotes the growth and duration of CyanoHABs (Carey et al., 2012; IPCC, 2014b). In shallow waterbodies, increased precipitation can also elevate the flux of legacy nutrients stored in the sediment to the surface (Paerl and Barnard, 2020). Extreme storms can promote CyanoHABs through wind forcing and vertical mixing, which causes sediment resuspension and the release of legacy nutrients (Wells et al., 2015). Decreased levels of precipitation can slow the flow of rivers and streams, leading to hydrologically stagnant waters, which promote the occurrence of CyanoHABs (Paerl and Huisman, 2008). Another climate driver of CyanoHABs is the increasing levels of dissolved carbon dioxide in waterbodies. Elevated carbon dioxide levels can lead to increased growth rates of cyanobacteria, which will intensify CyanoHABs (Raven et al., 2020; Verspagen et al., 2014; Visser et al., 2016).

CyanoHABs are also associated with anthropogenic eutrophication, such as agricultural land use, animal wastes, sewage and industrial and household use of products containing phosphorus and nitrogen (Le Moal et al., 2019). Nutrients from these processes enter waterbodies through runoff, storm drains, wastewater, and other direct discharges. Excess nutrients lead to enhanced growth of cyanobacteria, phytoplankton, and aquatic vegetation. Anthropogenic eutrophication is increasing due to land use changes, urbanization, and industry. The influence of eutrophication on CyanoHABs is difficult to distinguish from that of climate change (Wells et al., 2020).

CyanoHABs in California significantly threaten aquatic ecosystems and species that interact with them. CyanoHAB-related fish and wildlife kills are reported every year in California (SWRCB, 2021). People and domestic animals are exposed to cyanotoxins through drinking water, fish or shellfish consumption, or water recreational activities. In California, the number of public health advisories at recreational waterbodies has doubled since 2016 (SWRCB, 2021). Every year the state receives reports of illnesses in people and death in domestic animals following exposures to cyanotoxins (SWRCB, 2021). Economic losses due to CyanoHABs in the United States are estimated to be four billion dollars annually from impacts on drinking water, recreation, tourism, and aquatic food production (Kudela et al., 2015).

Invasive Agricultural Pests

Current warming has already enabled many invasive species worldwide, including insects, to extend their distributions into new areas (IPCC, 2022). Generally, the establishment and spread of an introduced species will be most successful when it has characteristics favored by the changing climate, such as being drought tolerant. While climate change increases the likelihood of the establishment, growth, spread, and survival of invasive populations, human factors such as the movement of goods and people and habitat disturbance are overwhelmingly more important (IPCC, 2014).

Temperature is probably the single most important environmental factor influencing insect behavior, distribution, development, survival and reproduction (Das et al., 2011). Generally, increasing air temperature is beneficial to insect pests. For those insects that breed continuously, as long as upper critical limits are not exceeded, rising temperatures accelerate every stage of an insect’s life cycle. The reduced time between generations leads to larger insect populations. In addition, warming temperatures can cause host crops to ripen early and prompt an earlier invasion by insect pests; at the same time, warming also lengthens the growing season, providing more opportunities for insects to inflict more damage on crops. During the winter, warmer temperatures will reduce insect death, allowing greater numbers to survive and reproduce in subsequent growing seasons (USDA, 2013).


Credit: Scott Bauer, USDA

Adult female oriental fruit fly, *Bactrocera dorsalis*, laying eggs by inserting her ovipositor in a papaya.

In California, new insect species arrive frequently. Warmer temperatures can allow such species to thrive where they previously could not survive. Invasive species include insects destructive to a wide variety of crops grown in the state, such as the *Bactrocera dorsalis,* also known as the Oriental fruit fly (OFF). OFF is endemic to Southern Asia and established in the Hawaiian Islands. These flies were first found in California in 1960 and have been reintroduced every year since 1966 through the movement of infested goods into the state. Economic impacts from establishment of this fly include damaged fruit and adverse impacts on native plants, increased pesticide use statewide by commercial and residential growers and loss of revenue due to export restrictions on fruit. In 2015 the estimated value of crops affected by OFF was over $16.4 billion (CDFA, 2018). It has been estimated that the cost of not eradicating OFF in California would range from $44 to $176 million in crop losses, additional pesticide use, and quarantine requirements (CDFA, 2018).

Climate change may be influencing OFF populations in California. Records from the California Department of Food and Agriculture (CDFA) and County Agricultural Commissioners of over 63,000 detection traps statewide for exotic fruit flies (CDFA, 2022), show that historical trappings of OFF were reported primarily between the months of June through December. In the past decade, detections have continued into January and February (2011 and 2015), suggesting that winter temperatures may be becoming more favorable for the insects (CDFA, 2018). Furthermore, earlier detections in April and May have become a common occurrence. These changes may be due to the earlier importation of infested fruit into the state (as fruit ripen earlier at their location of origin with warming temperatures). Likewise, warmer temperatures in California are likely to cause earlier ripening of host fruits, increase fly populations, and reduce temperature-related mortality. Scientists caution that biological responses are complex and cannot be predicted by single variables (e.g., increase in temperature or rainfall) (CDFA, 2013). Attributing changes in invasive pest populations to climate change is difficult without accounting for dynamic interactions between multiple species and climate variables as well as human influences. It should be noted that there have been fewer detections of pests during the COVID-19 pandemic, likely due to reduced travel and trade.

Eradication actions undertaken by CDFA and the US Department of Agriculture over the years have prevented invasive pest introductions from becoming permanently established. CDFA has initiated efforts to evaluate pest and invasive species movement with climate change using internal pest detection databases. This information informs the development of predictive models that assist CDFA's invasive species programs to effectively control invasive species and mitigate food crop loss (California Natural Resources Agency, 2016).

Bluetongue in Livestock

A warming climate can impact livestock directly by causing heat stress and indirectly by affecting vector-borne disease occurrence (IPCC, 2022). Bluetongue (BT) is a vector-borne viral disease of sheep, goats and cattle transmitted by biting midges of the arthropod genus *Culicoides.* Bluetongue infections cause high morbidity and mortality primarily in sheep. Disease outbreaks can also influence international trade, movement of livestock, animal production and welfare, and can have major economic consequences; for example, in Ontario, Canada the detection of infected cattle in 2015 caused the immediate suspension of exports of live animals, semen, and embryos, valued at nearly 300 million Canadian dollars (Mann, 2015).

Bluetongue disease occurs globally and is common throughout California, primarily in the San Joaquin and Sacramento River valleys (Moeller, 2016). Although BT is endemic in the US, climate change may alter the transmission of this and other similar arthropod-borne viruses, and increase the threat to both domestic and wild ruminants.

As discussed above, insects are sensitive to changes in temperature, suggesting they are likely to respond to climate change. Warming temperatures can alter the distribution of vectors and accelerate disease transmission (see *Vector-borne diseases* indicator). BT incidents have expanded northward and persisted in Europe and Canada, and have extended farther south than the traditional range into Victoria, Australia; in the United States, eleven previously exotic serotypes of BT virus have been detected since 1999 (serotypes are groups within a single species of microorganisms, such as bacteria or viruses, which share distinctive surface structures) (Mellor et al., 2008, Jimenez-Clavero, 2012; Maclachlan et al., 2018). Some of these non-endemic serotypes are being detected farther away from the southeastern United States where they are usually confined, suggesting increase in distribution and potential for persistence (Schirtzinger et al., 2018). Researchers suggest the *Culicoides* vector is especially responsive to climate change (Purse et al., 2005, 2008). In general, warm temperatures enhance the recruitment, development, activity and survival rates of *Culicoides* vectors. Scientists expect increases in temperature (particularly at night-time and in winter) — as well as precipitation (particularly in dry areas) — to lead to an increased geographical and seasonal incidence of BT virus transmission. Investigators modeling the distribution of

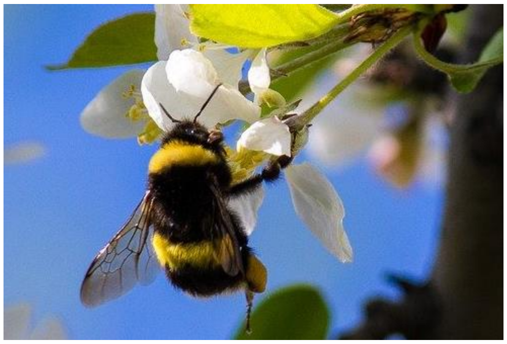
Culicoides in North America using future climate scenarios predict expansion of the vector beyond the current northern limit and increased risk of Culicoides-borne disease over the next several decades, particularly at the US-Canada border (Zuliani et al., 2015). The northward expansion of BT outbreaks in Europe in recent decades has been examined with climate-driven models that show increasing temperatures may explain aspects of this expansion (Guis et al., 2012) and predict a trend of increasing risk globally using future climate scenarios (Samy and Peterson, 2016). However, BT incidence is influenced by many factors, including vector ecology and transmission cycles, water availability, land use, and agricultural management, which hampers the ability to link climate change with disease outcome.

Research has continued on the ecology of the vector, and what climatic, environmental, and anthropogenic factors may affect disease transmission in California and in North America (Mayo et al., 2016 and 2020). This information will help direct risk assessment and targeted surveillance for presence of the virus, as well as potential mitigation strategies. Bluetongue occurrence in livestock is currently reportable to and monitored by the California Department of Food and Agriculture's Animal Health Branch.

Bumble Bee Populations

Bumble bees (genus *Bombus*) are major pollinators worldwide. By transferring pollen from one plant to another, they assist in fertilization and the production of seeds. They significantly contribute to the global agricultural industry and are essential to the environment (Hatfield and Jepsen, 2021). California is home to more than half (27) of the approximately 50 bumble bee species in North America — more than any other state in the country. Two of California's species, Franklin's bumble bee (*B. franklini*) and Crotch's bumble bee (*B. crotchii*), are largely endemic (Hatfield and Jepsen, 2021).

Bumble bee populations are declining worldwide (Cameron and Sadd, 2020), including eight of California's bumble bee species (Hatfield and Jepsen, 2021). The specific causes of bumble bee declines are largely unknown, although shifts in temperature and rainfall associated with climate change may be pushing bumble bees to their ecological limits (Kerr et al., 2015; Soroye et al., 2020). Other key threats that have been identified include pathogen infection (Cameron et al., 2016), insecticides (Wood and Goulson 2017), and habitat loss (Williams and Osborne 2009). These factors likely interact, creating synergistic effects and accelerating declines (Cameron and Sadd, 2020). Climate change, for instance, can influence bee diseases, parasites, predators, and pesticide use (Vercelli et al., 2021).


Bumble bees are native to California and important pollinators for the environment as agricultural crops.

A study that mapped 66 bumble bee species across North American and European sites from 1900 to 2014 found that increased frequency and severity of hotter temperatures between 1900-1974 and 2000-2014 correlated with increased local extinction rates, reduced colonization (spread of species to new areas), and decreased species richness (the number of different bumble bee species present together in local regions) (Soroye et al., 2020). Effects were independent of land use and were greatest in warmer parts of the Northern Hemisphere. Bumble bees have both contracted their ranges in warmer regions and expanded into cooler regions, although the extent of range loss far exceeds their range expansion. Because this study's analysis documented average change over a large area with many species, specific conclusions cannot be drawn at the state level. Comprehensive monitoring efforts are needed to better understand California bumble bee diversity and abundance statewide and the influence of climate change (Fisher et al., 2022).

Human Health

Aeroallergens

The prevalence of hay fever and asthma, including forms of the diseases known to be triggered by aeroallergens, is on the rise worldwide (Schmidt, 2016). The risk of respiratory diseases associated with aeroallergens (as well as ozone) is projected to increase in the future (Pörtner et al., 2022). Aeroallergens are airborne substances such as pollen or spores from molds that trigger allergic reactions in sensitized individuals. Most aeroallergens come from trees, weeds, and grasses that rely on wind to distribute their pollen or spores.

A growing number of experimental and field studies provide compelling evidence that warming temperatures and changing patterns of precipitation, along with increasing carbon dioxide (CO_2) levels, increase plant growth and pollen production (including pollen yields, pollen season timing and length, allergen content of pollen grains) (Anderegg et al., 2021; Anenberg et al., 2017; Ray and Ming, 2020; USGCRP, 2018; Zhang and Steiner, 2022; Ziska et al., 2019). Elevated CO_2 concentrations have also been experimentally shown to amplify allergenic mold spore production from leaves of timothy grass, a common livestock feed (Wolf et al., 2010).

Heavy short-term rainfall significantly reduces atmospheric pollen concentrations by wet deposition while changes in long-term precipitation patterns enhance or inhibit plant growth and alter total pollen production (Zhang and Steiner, 2022). Thunderstorms, which have become more frequent with warming ocean temperatures, have also been linked to increases in aeroallergen levels. Thunderstorms during the pollen season have been reported to trigger severe asthmatic symptoms in people with underlying asthma, hay fever, and allergic rhinitis (D'Amato et al., 2020; Ray and Ming, 2020). Scientists have hypothesized that during rainy storms, pollen grains are broken up into smaller allergenic particles that can induce severe asthma. There is also evidence that thunderstorms increase atmospheric mold spore concentrations and contribute to asthma-related hospital emergency visits (D'Amato et al., 2020).

Pollen and allergy seasons, already increasing in length and intensity, are expected to increase further as the climate warms (Nolte et al., 2018). Over the last several decades, warmer temperatures have been driving earlier (3 to 22 days) pollen season start dates for spring-flowering plants (e.g., deciduous trees), while late-flowering plants (e.g., grasses) have delayed pollen season start dates by up to 27 days (Zhang and Steiner, 2022). Since 1995, the ragweed pollen season has lengthened by more than 20 days in some parts of the United States (Rudolph et al, 2018). Eleven locations in the Northern Hemisphere showed a significant increase in pollen season duration over a 20-year period, with an average of 0.9 additional days per year (Ziska et al., 2019). Pollen records from 1990-2018 at 60 stations across North America, including five California cities, show an approximately 20-day advance and 8-day lengthening of the pollen season (Anderegg et al., 2021). Climate model simulations suggest that human-caused climate change was the dominant driver of the most recent changes (2003-2018).

A study has linked exposure to extreme heat events between 1997 and 2013 with an increased prevalence of hay fever among US adults (Upperman et al., 2017). Climate change is also linked to increased concentrations of air pollutants such as ozone, nitric oxide, and other volatile organic chemicals which may also be partially responsible for the increase in allergic respiratory disease reported over the past several decades (Ray and Ming, 2020).

Foodborne and Waterborne Infectious Diseases

Climate change is expected to adversely impact both food- and water-borne diseases. Factors such as increased air and water temperature as well as fluctuations in relative humidity and precipitation patterns could extend the time period and expand the geographical range of climatic conditions favorable to the survival, proliferation, and transmission of food- and water-borne microbial pathogens. As climate and the environmental landscape changes, so too will the residential, occupational, and recreational patterns of California residents, potentially increasing their opportunity to intersect with pathogens that formerly enjoyed comparatively restricted distribution, thus amplifying risk of infection.

Vibrio bacteria

Vibrio species bacteria, which exist naturally in coastal waters and are associated with shellfish, increase in numbers as seawater temperature rises and salinity profiles change (e.g., due to sea level rise). Illness occurs among persons who eat raw shellfish such as oysters and persons with fresh skin wounds exposed to contaminated seawater or shellfish. Although uncommon, *Vibrio vulnificus* is a leading cause of death from seafood contamination in the US. And globally, toxigenic *Vibrio cholerae* remains the cause of cholera outbreaks and epidemics, often waterborne. Rapidly changing global oceanic conditions have pushed *Vibrio* geographical ranges farther north into historically colder regions (Vezzulli et al., 2016), with detection of Vibrio in areas where the bacteria were previously absent or rarely reported (Baker-Austin et al., 2010). The spread of Vibrio will increase the potential exposure of shellfish consumers and recreational ocean water users throughout the coastal regions of the US, including in California.

Legionnaires' disease (LD)

Legionnaires' disease (LD) is a severe form of pneumonia usually caused by inhalation of aerosolized water containing *Legionella* bacteria. *Legionella* are found naturally in freshwater sources and can grow and spread in artificial water systems such as cooling towers, hot water tanks, hot tubs, decorative fountains, and large buildings with complex water systems. People are exposed to the bacteria when devices aerosolize the contaminated water.

LD is more common during warm summer months, with increased rates of LD during periods of increased relative heat, humidity or greater rainfall (Fisman et al., 2005, Gleason et al., 2016; Hicks et al., 2007; Rickets et al., 2009; Simmering et al., 2017). This is likely due to both ecological and human factors. *Legionella* proliferate in warm, wet environments with temperatures between 77 and 113° F (CDC, 2020; Yu et al., 2019). Increased numbers of *Legionella* in the environment, including in water supplies (e.g., water reservoirs) could facilitate further downstream amplification within artificial water systems used by humans and subsequent exposure (Walker, 2018). In artificial water systems already contaminated with *Legionella*, these conditions encourage bacterial proliferation. Increased use of cooling devices such as cooling towers during warm weather increase the aerosolization of *Legionella*. Once aerosolized in water, warm and humid environments increase the distance that aerosolized water can travel as well as survival of *Legionella* within that water, increasing the potential infectious range.

Increased frequency and severity of extreme weather events and natural disasters may also lead to intrusion of contaminated water into artificial water systems (e.g., damaging water infrastructure, flooding events contaminating water supply; Brigmon et al., 2020; Walker 2018). Storm events may themselves enhance conditions for *Legionella* growth in water systems by favorably altering oxygen levels and biological and chemical makeup of the water supply (Brigmon et al., 2020). Droughts may cause further reliance on alternative water collection and storage methods (e.g., rainwater collection), which can increase the risk of *Legionella* growth due to favorable environmental conditions including contamination, stagnation and warm outdoor temperatures (Walker, 2018).

Zoönoses

"Zoönosis" is the classic term for an infectious disease that is shared between humans and animals. The roles that animals play in "sharing" zoönoses are varied. Animals can serve as the incubator from which bacteria or viruses emerge that can cause illness in humans. Measles, AIDS, and most recently COVID-19 are examples of diseases that originated in animals—cattle, non-human primates, and bats, respectively—but have evolved to be efficiently transmitted directly between humans (Düx et al., 2020; Furuse et al., 2010; Lytras et al., 2021; Sharp et al., 2011). Animals can also serve as a reservoir for microbial pathogens, maintaining infection but without suffering any ill-health themselves. *Borrelia burgdorferi*, the bacterial agent of Lyme disease, and Sin Nombre virus, the cause of hantavirus pulmonary syndrome (HPS), are both maintained in wild mice. Infected mice do not develop disease but can transmit the pathogens to humans indirectly (via ticks for Lyme disease) or directly (through aerosolized urine or feces for HPS). Finally, some zoönotic pathogens cause disease in both human and animal hosts; for example, the bacterial agents of anthrax and plague can cause severe and often fatal disease in wild animals, domestic animals, and humans.

Transmission of disease agents between humans and animals is in part dependent on their respective populations' distributions, densities, and proximity. For animals, these population dynamics are defined by the type of habitat—or habitats—in which the animal exists. Habitat—food, shelter, water—is largely determined by the prevailing climatic conditions. Significant changes to these conditions can alter the character of a geographic region to render it more or less conducive to the species' survival. Animals may adapt to changing environments through the random mechanism of natural selection. However, the dramatic environmental transformations wrought by anthropogenic climate change outpace the ability of most species to evolve. The only other responses available to most animal species are to reduce their population to a size that the altered habitat can continue to support, or to adjust their geographic range to areas that remain hospitable. For California, these climatologic changes will likely favor those species that can endure higher temperatures and more arid conditions, or can relocate to regions that remain relatively cooler and wetter. Both responses could change the frequency and intimacy with which some animals and humans interact, enhancing opportunities for zoonotic disease transmission (Heffernan, 2018; Hoberg and Brooks, 2015; Lorentzen et al., 2020; Morand and Walter, 2020).

Hotter, drier conditions can impact the size or density of zoönotic animal host and vector populations. Sustained elevated temperatures result in mosquitoes maturing more quickly and lead to larger populations (Mills et al., 2020). Protracted drought may reduce aquatic breeding habitat for some mosquito species, but can benefit others by transforming previously free-flowing rivers and creeks into stagnant pools (Bartlow et al., 2019). Changes to local conditions that favor some generalist species but reduce or eliminate species with unique habitual needs can reduce local biodiversity, potentially to the benefit of zoönotic disease reservoirs. For example, reduced diversity of bat species can facilitate perpetuation of rabies virus, leading to greater incidence among viable host species and increased risk of transmission to non-hosts such as humans (Patil et al., 2017).

Species that are unable to adapt to hotter or drier conditions may adjust their ranges toward higher elevations or polar latitudes. These movements could alternatively introduce zoönotic diseases into previously unaffected human populations, or dissociate disease agents from human contact. For example, the bacteria that cause plague (*Yersinia pestis*) and tick-borne relapsing fever (*Borrelia hermsii*) in California are maintained in wild rodents and transmitted via flea and tick bite, respectively; with incrementally hotter average temperatures, their current foci in mid- and upper-elevations of the Sierra Nevada may shift to higher and constricted elevations, possibly farther displaced from areas where humans reside or visit. Approximately half of the 28 species surveyed in Yosemite National Park—including squirrel (*Spermophilus* spp.) and chipmunk (*Tamias* sp.), reservoir species for Y. pestis—had upslope shifts of range limits compared with similar surveys conducted approximately 100 years earlier, when minimum temperatures were 3°C lower (Moritz et al., 2008). This shift from temperate to alpine regions parallels a similar shift of hosts and vectors of zoönoses previously concentrated in tropical and subtropical latitudes to temperate regions. In the last decade, vampire bats (*Desmodus rotundus*) and mosquitoes (*Aedes aegypti*, *Ae. albopictus*) have encroached northward from Latin America, threatening local transmission of rabies and arboviruses (e.g., Zika, Chikungunya, dengue), respectively, in North America (Hayes and Piaggio, 2018; Iwamura et al., 2020; Ryan et al., 2019).

Loss of natural food, water, or harborage may stimulate some animal species to seek these essentials from areas of human development and residence. Deforestation, including via climate-enhanced mega-wildfires, has been cited as possibly contributing to displacement of bats from natural roosting sites in favor of concentration around human habitations, leading to the emergence of bat-borne zoönotic viruses such as Nipah and Hendra (Halpin et al., 2000) and the SARS-type coronaviruses (Afelt et al, 2018). Water stored near human communities may attract wild mammals such as skunks, raccoons, and coyotes, increasing the peri-residential risk of zoönoses such as rabies and Toxocara and Baylisascaris larval migrans. Standing water in eaves, yards, and patios can provide habitat for mosquito breeding, increasing peri-residential risk of West Nile virus and other mosquito-borne arboviruses.

As hospitable habitat contracts, individual animals are drawn into more confined areas, resulting in more frequent competition and contact which enables transmission of zoönotic pathogens. In 2021, 29 cases of salmonellosis among human residents of eight states, including California, were traced to unusual concentrations of songbirds densely congregating at backyard feeders and bird baths (CDC, 2021), possibly as a result of reduced natural food and water sources. Avian influenza viruses have traditionally resided in and emerged from wild birds, particularly migratory waterfowl. As drought and development displace natural wetlands along avian flyways, this traditional breeding ground for avian influenza might diminish. If wild waterfowl seek alternative water and food resources near poultry operations, this proximity can enhance transmission of influenza viruses to domestic poultry and one step nearer to humans (Gilbert et al., 2008).

The impact of climate change on zoönotic disease epidemiology in California and the western U.S. has yet to be fully understood. Effective preparation will require an integrated collaboration of human health and animal health professionals and environmental scientists to identify and respond to climate-induced changes in zoönotic disease incidence and distribution in a timely, comprehensive, and effective manner.

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[*] Note: The findings and conclusions in this report are those of the author and do not necessarily represent the views or opinions of the California Department of Public Health or the California Health and Human Services Agency.

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