Delta Stewardship Council

A CALIFORNIA STATE AGENCY

DELTA ADAPTS: CREATING A CLIMATE RESILIENT FUTURE

TECHNICAL MEMORANDUM

CROP YIELD AND AGRICULTURAL PRODUCTION

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CHAPTER 1. BACKGROUND

1.1 Overview

Climate change presents a great risk to global food security (IPCC 2019). California agriculture, which produces much of the vegetables, fruits, and nuts in the United States (Pathak et al. 2018) and is a significant part of California's economy, is also at risk from climate change. Recent climate change syntheses and vulnerability assessments for California highlight that statewide agricultural diversity and productivity will be broadly impacted by climate change. The most substantial changes include shifts in the timing and volume of water flow in winter, warmer and longer summers, fewer winter chill hours, decreased soil moisture and increased soil salinity, increased frequency and intensity of extreme events (flood events, multiyear droughts), and increased atmospheric carbon availability (Houlton et al. 2018, Medellín-Azuara et al. 2018).

Climate change threats more unique to agriculture in the Sacramento–San Joaquin Delta and Suisun Marsh (hereafter, the Delta) also include sea level rise and salinity intrusion, which will challenge the usability of irrigation water, reduce arability, and increase flood risk to subsided Delta islands (Dettinger et al. 2016, Deverel et al. 2015, Council 2018, Medellín-Azuara et al. 2014). California statewide vulnerability assessments and scientific research suggest that climate change will affect the yields of predominant Delta crops, with some perennial crops experiencing significant yield decline (e.g., almonds and cherries; Lobell et al. 2006, Pathak et al. 2018). Additionally, the Delta Protection Commission recently completed a regional synthesis of climate change-induced biophysical impacts on crop production and crop suitability (Fairbanks et al. 2019). The Delta Stewardship Council's climate change initiative, called Delta Adapts: Creating a Climate Resilient Future will quantify the amount of agricultural land by crops that are anticipated to be flooded under various climate change scenarios, and the cost of flooded agricultural land on the regional economy in the vulnerability assessment prepared under separate cover. **This Crop Yield and Agricultural Production Technical Memorandum (TM) summarizes potential biophysical impacts of climate change to crop production and suitability and discusses agro-social and agro-economic considerations particular to the Delta.**

While projecting climate is not without challenge, projecting social and economic vulnerabilities to changing conditions can be even harder. This becomes more evident in agriculture, where decisions are often made on shorter-term scales, and social and market factors may have a stronger influence than long-range climate projections. Nonetheless, climate changes and their indirect effects will likely increase crop production vulnerability.

1.2 Delta Agriculture: Setting and Ongoing Challenges

Agriculture is the dominant land use in and cultural backbone of the Delta, driving the local economy and surrounding communities, and providing most of the employment in the Primary Zone (Medellín-Azuara et al. 2012). Agriculture adds great cultural value for Delta residents, farmers, and visitors, a value that often spans generations. Beginning in the 1850s, the Delta's islands were reclaimed from tidal marshes for agricultural development, and the Delta rapidly became California's first developed agricultural region. The Delta—and Suisun Marsh, to a lesser degree—was and continues to be suitable for farming because of its high-quality soils, nearby water supply through its channels, and a moderate Mediterranean climate mediated by proximity to the Pacific Ocean. Although California's climate is characterized by frequent extremes (Swain et al. 2018) and vulnerable to multiyear droughts, the Delta has typically mild, wet winters and hot, dry summers combined with the fertile soils from former wetlands. With these factors combined, most of the Delta is considered Prime Farmland, and a significant remainder of the land is termed Farmland of Statewide Importance, or Farmland of Local Importance (Table 1, DOC 2016).

Delta agriculture covers most of the Delta landscape and provides food for local and state markets. Dozens of crops are currently grown in the Delta, covering approximately 55 percent of its land (about 415,000 out of 800,000 acres, DPC 2020). In 2016, about 50 percent of the Delta was dominated by alfalfa, corn, and pasture, but the region is also a prominent source of specialty crops: wine grapes, truck crops (processing tomatoes and squashes), wheat, tree nuts and fruits, and rice (DPC 2020). Some Delta farmers are turning to carbon market farming with crops such as rice or managed wetlands (Deverel et al. 2017). While still a distinct minority, the Delta currently supports about 7,500 acres of rice and 1,600 acres of carbon-farming managed wetland (Pitzer 2020). Higher-value permanent crops, such as vineyards and orchards, are increasingly covering more acreage in the Delta, replacing annual crops (DPC 2020). The pace is extreme for some crops; from 2009 to 2016 almonds increased acreage by 400 percent, walnuts 82 percent, and wine grapes by 38 percent. In the same period, corn (-22 percent), oats (-57 percent), and asparagus (-73 percent) are among the declining crops by acreage (DPC 2020). Climate change impacts should be of special concern to farmers when investing in crops that require years to become viable and may also become subject to yield loss due to climate or water quality.

Land subsidence, flood risk, irrigation and drainage, and pumping costs, are unique challenges to Delta farming that may be exacerbated by a changing climate. Oxidation of peat soil, wind erosion, and use of heavy equipment has caused significant land subsidence (up to 25 feet on some islands), which increases pressure on levees in a system already vulnerable to winter and spring flooding. In addition to affecting levee integrity, subsidence also leads to under-levee water seepage and waterlogged soils, requiring farmers to regularly pump water off islands (Water Education Foundation 2014). Droughts do not generally impact surface water levels in tidally influenced parts of the Delta, but loss of channel capacity due to sedimentation coupled with severe multiyear droughts can decrease water depths in some parts of the Delta. Loss of channel capacity can affect access to irrigation water, raising costs for some farmers who must adjust their intakes and/or pump water onto islands instead of relying on passive water transportation. Further, reduced channel depth promotes invasive weeds, reduces dissolved oxygen, and increases the extent and duration of harmful algae blooms. The State and Federal Water Projects (water conveyance systems that transfer water from the Delta to other service areas in California) are required to release water to prevent intrusion of saline water eastward into the Delta. However, decreased freshwater flows during severe droughts can allow salinity intrusion further east, which can harm crops with low tolerance for salinity (Maas and Grattan 1999). Emerging regulatory prescriptions include increased flows from the watershed through the Delta, which could substitute for some currently required Project reservoir releases, however, decreasing the risk for salinity intrusion under current hydrological and sea level conditions. All these challenges will interact and potentially compound with the changing climate and affect climate vulnerability for Delta agriculture.

Figure 1: Agriculture in the Context of the Delta

Table 1: Land use and soil categories in the Delta

Land Use and Soil Categories	Definition	Acres (2016)	Percentage of total
Prime Farmland	Best quality farmland for sustained high yields	377,613	45.0%
Farmland of Statewide Importance	Similar to prime farmland, but with minor shortcomings	32,182	3.8%
Farmland of Local Importance	Land of importance to the local economy	52,492	6.2%
Unique Farmland	Farmland of lesser quality soils used to produce the state's leading crops	25,236	3.0%
Farmland of Local Potential	Land that if cultivated, would contribute to the local economy	2,300	0.3%
Grazing Land	Land on which the existing vegetation is suited for grazing	59,626	7.1%
Confined Animal Agriculture	Lands that include poultry facilities, feedlots, dairy facilities, and fish farms	1,292	0.2%
Rural Residential Land	Residential areas of one to five structures per 10 acres	1,776	0.2%
Semi-Agricultural and Rural Commercial Land	Includes farmsteads, non-cultivation agricultural or equine structures, unpaved parking areas, and campgrounds	2,331	0.3%
Urban and Built-Up Land	Developed land with a building density of at least one unit per 1.5 acres	79,130	9.4%
Vacant or Disturbed	Channelized canals and open field areas that are used for various industrial or recreational activities	3,693	0.4%
Nonagricultural and Natural Vegetation	Natural vegetation communities, managed wetlands, and small water bodies	16,450	2.0%
Water	Perennial water bodies with an extent of at least 40 acres	82,530	9.8%
Other Land	Land not included in any other mapping category	103,284	12.3%

Source: Adapted from California Department of Conservation’s Farmland Mapping and Monitoring Program, DOC 2016. The first four categories (totaling 487,523 acres) have the highest soil ratings and current land use and are thus the highest valued categories.

1.3 Planning and Regulatory Setting

The Delta Adapts Initiative will address the Council's legislative charge to achieve the coequal goals for management of the Delta (Water Code section 85020), and "reduce risks to people, property, and state interests in the Delta by effective emergency preparedness, appropriate land uses, and investments in flood protection" (Wat. Code section 85020(g)) as these goals relate to climate change impacts. "'Coequal goals' means the two goals of providing a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem. The coequal goals shall be achieved in a manner that protects and enhances the unique cultural, recreational, natural resource, and agricultural values of the Delta as an evolving place." (CA Wat. section 85054).

The Delta Plan (Council 2013) contains a set of regulatory policies pertaining to agriculture:

G P1. Detailed Findings to Establish Consistency with the Delta Plan (23 Cal. Code of Regs. section 5002)

> *(b) Certifications of consistency must include detailed findings that address each of the following requirements:*
>
> > *(2). Covered actions not exempt from CEQA must include all applicable feasible mitigation measures adopted and incorporated into the Delta Plan as amended April 26, 2018 (unless the measure(s) are within the exclusive jurisdiction of an agency other than the agency that files the certification of consistency), or substitute mitigation measures that the agency that files the certification of consistency finds are equally or more effective.*

There are several mitigation measures protecting agriculture in the Delta Plan, including requiring design of projects to minimize the loss of the highest valued agricultural land to the greatest extent feasible, and mitigating the permanent conversion of farmland at a target ratio of 1:1. These mitigation measures are required to be incorporated per Policy G P1(b)(2).

DP P1. Locate New Urban Development Wisely (23 Cal. Code of Regs. section 5010)

> *(a) New residential, commercial, and industrial development must be limited to the following areas, as shown in Appendix 6 and Appendix 7:*
>
> > *(1) Areas that city or county general plans as of May 16, 2013, designate for residential, commercial, and industrial development in cities or their spheres of influence;*
> >
> > *(2) Areas within Contra Costa County's 2006 voter-approved urban limit line, except no new residential, commercial, and industrial development may occur on Bethel Island unless it is consistent with the Contra Costa County general plan effective as of May 16, 2013;*
> >
> > *(3) Areas within the Mountain House General Plan Community Boundary in San Joaquin County; or*

(4) The unincorporated Delta towns of Clarksburg, Courtland, Hood, Locke, Ryde, and Walnut Grove.

(b) Notwithstanding subsection (a), new residential, commercial, and industrial development is permitted outside the areas described in subsection (a) if it is consistent with the land uses designated in county general plans as of May 16, 2013, and is otherwise consistent with this Chapter.

(c) For purposes of Water Code section 85057.5(a)(3) and section 5001(j)(1)(E) of this Chapter, this policy covers proposed actions that involve new residential, commercial, and industrial development that is not located within the areas described in subsection (a). In addition, this policy covers any such action on Bethel Island that is inconsistent with the Contra Costa County general plan effective as of May 16, 2013. This policy does not cover commercial recreational visitor-serving uses or facilities for processing of local crops or that provide essential services to local farms, which are otherwise consistent with this Chapter.

(d) This policy is not intended in any way to alter the concurrent authority of the Delta Protection Commission to separately regulate development in the Delta's Primary Zone.

Policy DP P1 essentially limits urban development of residential, commercial, and industrial uses to areas that were designated for such uses in adopted regulatory documents as of 2013, and as a result, protects existing land designated for agricultural use.

DP P2. Respect Local Land Use When Siting Water or Flood Facilities or Restoring Habitats (23 Cal. Code of Regs. section 5011)

(a) Water management facilities, ecosystem restoration, and flood management infrastructure must be sited to avoid or reduce conflicts with existing uses or those uses described or depicted in city and county general plans for their jurisdictions or spheres of influence when feasible, considering comments from local agencies and the Delta Protection Commission. Plans for ecosystem restoration must consider sites on existing public lands, when feasible and consistent with a project's purpose, before privately owned sites are purchased. Measures to mitigate conflicts with adjacent uses may include, but are not limited to, buffers to prevent adverse effects on adjacent farmland.

Policy DP P2 protects agriculture by requiring that new water facilities, flood management structures, and habitat restoration respect local land uses such as existing agricultural land and operations.

In the time since the 2013 adoption of the Delta Plan, research on climate change has advanced significantly and has implications for the Council as it seeks to achieve the coequal goals. Delta Adapts provides critical support to the Council and interested stakeholders in improving the understanding of climate change risks and potential adaptation strategies for the Delta region to continue to protect agricultural use

Chapter 2. Biophysical Impacts to Crop Yields

2.1 Climate Change Science and Agriculture

Climate change is expected to intensify current climate variabilities and extremes in California, including in the Delta (Dettinger et al. 2016). The biophysical component of agricultural production will be most impacted by increases in annual temperatures, increases in winter minimum temperatures, and exposure to extreme precipitation events– both floods and droughts. The Council's Climate Change and the Delta: A Synthesis provides a full review of expected climate changes in the Delta (Council 2018). The economic impacts of arable land loss to sea level rise, storm surge, and levee maintenance are discussed in the economics analysis within the Vulnerability Assessment.

This Crop Yield and Agricultural Production TM synthesizes the potential changes that could occur between 2030 to 2100 that are most impactful to agricultural performance and crop yield outcomes including:

1. Changing air temperatures
    - Hotter and longer summers
    - Warmer winters and fewer chilling hours
2. Changing precipitation patterns and sea level rise
    - Watershed water supply and Delta irrigation water
    - Frequency and intensity of multiyear droughts, sea level rise, and impacts to water quality
3. Increasing Extremes
    - Increased frequency and intensity of extreme heat
    - Increased frequency and intensity of extreme high precipitation and flood risk
4. Indirect impacts and interactions
    - Carbon availability and CO_2 fertilization
    - Pests, weeds, and diseases
    - Impacts to animal pollinators

2.2 Projected Climate Change Impacts to Delta Crops

The climate change factors listed above will contribute to yield response in Delta crops. Crop models are specific to a region and set of parameters. Models for the greater Sacramento and San Joaquin river valleys are the closest approximation when studies particular to the Delta are not available. However, Delta's open water and San Francisco Bay influence result in relatively mild climate changes compared to the rest of the Central Valley. Regional yield models based on predicted changes across the Central Valley indicate that yield changes vary by crop, with losses expected for crops that occupy over half of current acreages (Table 2 , Figure 3). Across the state, changing water management and a less predictable water supply will drive yields (Jackson et al. 2011, Medellín-Azuara et al. 2018), but extreme heat and flood events will also contribute to yield losses, especially in the latter half of the century (Deschenes and Kolstad 2011, Pathak et al. 2018). Rising air temperatures and changing precipitation patterns will increase physiological stress, thereby increasing susceptibility to pests, disease, and weeds (Pathak et al. 2018). Despite these risks, some studies suggest that abundant carbon dioxide supply may boost yields and lessen some of the negative consequences of climate change, but these gains may not be substantial (Blanc and Reilly 2017). These climate change–crop yield studies, summarized below, were developed for crops statewide but can apply to crop vulnerability in the Delta.

2.2.1 Air Temperature

Agricultural processes in the Delta are optimized with irrigation through California's variable rainfall and hot summers but may not withstand climate changes through 2100. Depending on emissions scenarios, models, and sub-region, Delta seasonal temperatures are likely to increase 4°F (summer maximum) and 2.3°F (winter minimum) by 2030 and 9.7°F (summer maximum) and 8.6°F (winter minimum) by 2100 (ensemble mean of four models on Emissions Scenario 8.5, Fairbanks et al. 2019). By 2100, the Delta's mean annual maximum temperature could increase between 2.2°F and 4°F (Fairbanks et al. 2019). Throughout the century, the western and northern Delta regions are estimated to have the highest summer temperatures, and the southern and northern Delta regions are predicted to have the highest winter temperatures (Fairbanks et al. 2019). For the greater Central Valley, the mean annual maximum temperature by 2100 is projected to be warmer than the Delta and Suisun Marsh by about 2.0°F (Cal-Adapt 2017). In this way, the Delta and Suisun Marsh may serve as a thermal refuge for crops that would otherwise be subject to more temperature stress elsewhere in the Central Valley.

Temperature influences metabolic processes and photosynthesis rates that control evapotranspiration and water needs, overall growth, leaf morphology and development, nutritional quality and flavor, flowering and pollination timing, and fruit production (Cavagnaro et al. 2006, Tabari et al. 2011). By 2100, rising air temperatures will influence each crop differently, but will likely result in overall reduced yields of the current crop assemblage in the Delta. In addition, increased temperature variability tends to reduce yields, such as with almonds, wine grapes, hay, walnuts, table grapes, and cherries (Lobell et al. 2006).

A literature review of climate change impacts on California crops suggests that temperature is a major factor , and will impact crops grown in the Delta (Table 2 and Figure 3).

2.2.1.1 Hotter and Longer Summers

Hotter, longer summers will extend the growing period and accelerate growth by increasing the rate of metabolic processes if other environmental stresses are controlled for. Accelerated growth occurs if the increased temperatures are within the optimal range for the crop species, but exposure to super-optimal temperatures reduces yields. Positive effects of warmer daytime temperatures may be offset by increased water demands through accelerated crop evapotranspiration, increased overnight respiration rates, and reduced soil moisture (Lobell et al. 2006, Pathak et al. 2018). Crop models suggest that reduced yield from high temperatures is typically caused by water stress. Increased irrigation would buffer against yield declines (Schauberger et al. 2017). The Delta's water supply availability, relative to other agricultural areas in the Central Valley, may set it up as uniquely able to compensate for higher air temperatures if water quality remains favorable. Warm nighttime temperatures can also reduce fruit or grain quality or productivity (Walthall et al. 2012).

Accelerated growth may positively influence plant size and time to harvest for many crops, but quality may be negatively impacted. For example, alfalfa, which covers about 19 percent of Delta farmland, may experience improved yields with hotter summers, but with reduced quality (Medellín-Azuara et al. 2018, DPC 2020). Higher minimum temperatures may decrease rice yields, while higher maximum temperatures may lead to yield increases but also increases in rice grain chalkiness, which decreases the amount of marketable rice (Zhao and Fitzgerald 2013). While wine grape yields may be negligibly affected by hot temperatures, extreme heat negatively impacts flavor, aroma, and color (Nicholas et al. 2011).

Delta crops are variably vulnerable to rising air temperatures. Warmer temperatures will favor some Delta crop yields, including alfalfa, tomatoes, and sweet potatoes (Cavagnaro et al. 2006, Fairbanks et al. 2019). Tomato yields may increase or be less affected by warmer summers once fruit has set, with a longer growing season and accelerated time to harvest (Jackson et al. 2011, Lee et al. 2011, Pathak and Stoddard 2018). More research is needed to draw conclusions on various truck vegetables (e.g., onion, garlic) climate vulnerability (Kerr et al. 2018, Pathak et al. 2018). Fruits generally respond negatively to hotter summers, especially during fruit development stages. Delta fruits, including, cherries, and table grapes, are expected to have reduced yields of 5 to40 percent as modeled in the Central Valley (Pathak et al. 2018, Kerr et al. 2018). Corn, a Delta crop with significant acreage, has yield reductions at temperatures above 84.2°F (Schlenker and Roberts 2009). Notable heat-tolerant fruits include wine grapes, almonds, and walnuts, which may have little change or improved yields with warmer summers, yet reduced time to maturity (Lobell et al. 2006, Webb et al. 2012).

2.2.1.2 Warmer Winters and Fewer Chilling Hours

Warm winters will negatively impact many perennial crops currently established in the Delta, but also reduce the incidence of frost damage (Reilly and Graham 2001). Olives and citrus, which are limited by minimum temperatures, may benefit from warmer winters in the Delta, resulting in yield increases (Reilly and Graham 2001, Denney et al. 1985). Warm winters are expected to reduce yields in wine grapes, strawberries, and most fruit and nut trees (Lobell and Field 2011).

Winter minimums are expected to increase faster than seasonal averages or maximums, which will be detrimental to crops that require a certain number of chilling hours below 45°F. Most fruit and nut trees require a threshold of chilling hours to break dormancy, achieve simultaneous flowering and pollination, and maintain predictable high-quality yields. Chilling hours may better predict yields than growing season temperatures (Lobell and Field 2009, Pathak et al. 2018).

Annual accumulation of winter chill hours in California has already decreased (Baldocchi and Wong 2008). By 2050, it is suggested that the Delta may have 550 to 650 chilling hours, which is suitable for almond, fig, olive, persimmon, pomegranate, chestnut, pecan, and quince trees, but *not* pear, cherry, apple, apricot, kiwifruit, peach, nectarine, plum, or walnut trees (Luedeling et al. 2009). By 2100, the Delta is not likely to have sufficient chilling hours to ensure viability of many orchards and is projected to range from 250 to 400 chilling hours. Therefore, by 2100, the remaining fruit and nut trees that may be viable in the Delta are almond, fig, olive, persimmon, and pomegranate trees (Ibid). Given long lead times, farming may able to adapt with crop choices that reflect climate change predictions.

Warmer winters will decrease the occurrence of tule fog, a thick wintertime ground fog which farmers historically relied on to limit evapotranspiration November to March (Gray et al. 2019). Tule fog is also a critical factor in winter chill that fruit trees require in the Central Valley (Ibid).

A summary of anticipated climate change impacts (as predicted for the greater Central Valley, which is anticipated to be about 2°F higher than the Delta) on current Delta crops, largely driven by temperature, is illustrated below in Table 2 and Figure 3.

Figure 2: Farmland in the Suisun Marsh area

Table 2: Delta crop yield impacts under climate change, based on predictive modeling for temperature change in the greater Central Valley.

Land Use Type	Acres	Yield Under Climate Change	Expected Timeframe	Source
Alfalfa	77,576	Small growth	End-of-century	Pathak et al. 2018
Almonds	15,651	Medium decline⋇	Mid-century End-of-century	Lobell and Field 2011, Pathak et al. 2018
Asparagus	1,964	Medium decline⋇	Mid-century	Medellín-Azuara et al. 2018
Bush Berries	1,253	Unknown	Not applicable	Not applicable
Carrots	182	Medium decline	Mid-century	Medellín-Azuara et al. 2018
Cherries	2,927	Large decline	Mid-century	Lobell and Field 2011
Citrus	6	No change	Mid-century	Lobell and Field 2011
Corn	82,392	Small decline	End-of-century	Lee et al. 2011
Cucurbit	3,593	Medium decline	Mid-century	Medellín-Azuara et al. 2018
Forage Grass	5,874	Small growth	Mid-century	Izaurralde et al. 2011
Olives	1,628	Unknown	Not applicable	Not applicable
Pasture	46,878	Small decline	Mid-century	Medellín-Azuara et al. 2018
Pears	5,429	Decline*	Mid-century	Luedeling et al. 2009
Pistachios	274	Decline†	End-of-century	Pathak et al. 2018
Potatoes	4,054	Small decline	Mid-century	Medellín-Azuara et al. 2018
Rice	7,468	Small decline	End-of-century	Pathak et al. 2018
Safflower	12,852	Small decline	End-of-century	Pathak et al. 2018
Sunflower	591	Small/large decline	End-of-century	Pathak et al. 2018
Tomatoes	29,181	No/small decline	End-of-century	Pathak et al. 2018
Truck Crops	2,773	Medium decline⋇	Mid-century	Medellín-Azuara et al. 2018
Vineyards	41,613	No/small decline (wine) Small/medium decline (table)	End-of-century	Pathak et al. 2018
Walnuts	4,580	Small decline	End-of-century	Pathak et al. 2018
Young orchard	214	Small growth	Mid-century	Medellín-Azuara et al. 2018

Source: Acres of land use type are adapted from 2016 CACASA and 2016 LandIQ from DPC 2020.

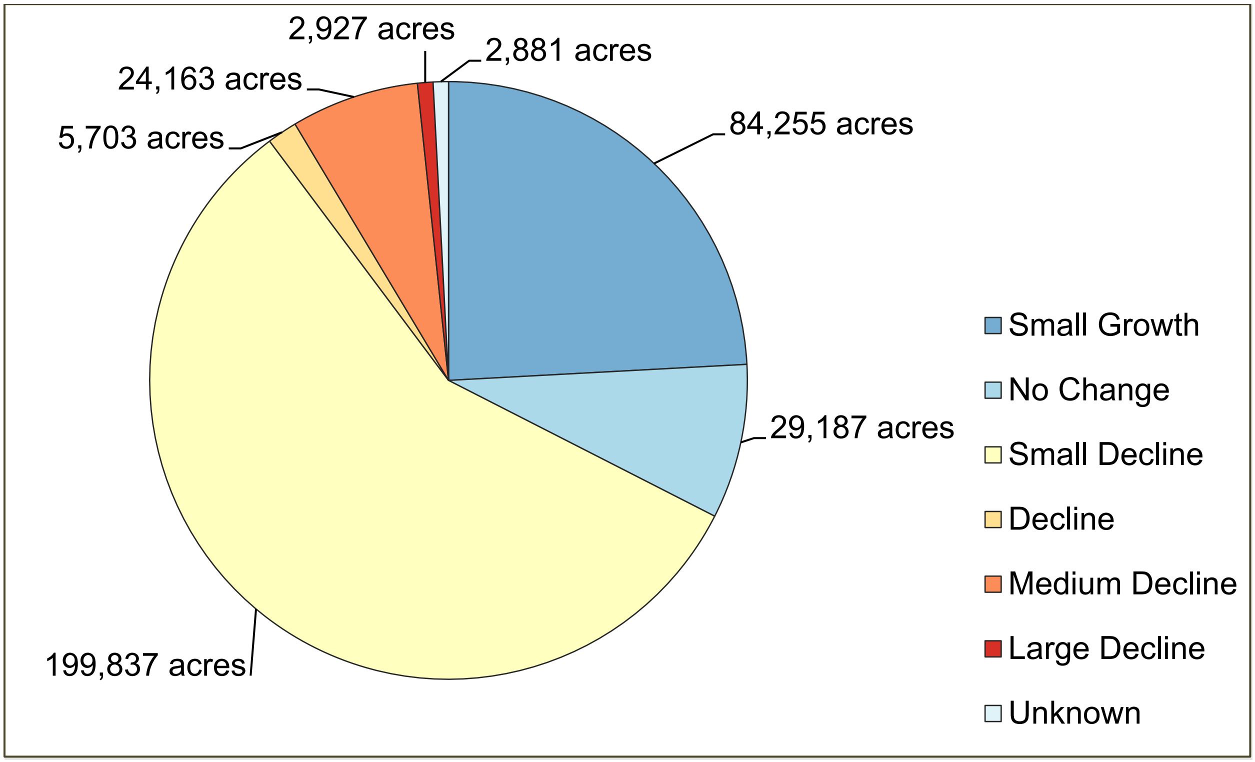
Yields key: Small growth <+10%, No change ~0%, Small decline >-10%, Medium decline >-20%, Large decline <-20%.

⋇Based on yield declines for vegetables as a category, individual crops may vary.

*In Luedeling et al. 2009, the authors predict pear yield declines based on declining winter chills, but do not make predictive modeling on the percentage of the decline.

†In Pathak et al. 2018, the authors predict pistachio yield declines based on declining winter chills, but do not make predictive modeling on the percentage of the decline.

Figure 3: Delta crop yield impacts under climate change, based on predictive modeling for temperature change in the greater Central Valley.



Source: Acres of land use type are adapted from 2016 CACASA and 2016 LandIQ (DPC 2020); see Table 2 for peer-reviewed sources of predictive change and expected timeframe.

2.2.2 Precipitation Patterns and Sea Level Rise

In the Delta and its watershed, timing and volume of precipitation is expected to be constricted within a shorter period in winter, with a greater percentage of precipitation falling as rain within extreme events instead of being stored as snow at high elevations, elevating flood risk, increasing summer water scarcity in the watershed, and potentially decreasing water quality in the Delta (Rhoades et al. 2018). Multiyear droughts will become more frequent and unpredictable, suggesting that surface water conservation and efficiency measures previously required during drought years may always be advised (Diffenbaugh et al. 2015). The success of California agriculture in the greater Central Valley is dependent on water applications from interdependent storage and irrigation systems that will be affected by changing precipitation patterns. Even during the most severe droughts, water availability in the Delta is not affected, however, because of the Delta's tidal influence, water quality may wane during droughts if freshwater flows are reduced and sea water penetrates further into the Delta. Earlier timing of runoff and greater precipitation variability will alter water storage and management regimes, which may negatively affect water quality for users in the Delta.

2.2.2.1 Delta Irrigation Water and Rainfall Patterns

Most agricultural water diversions in the Delta rely on senior water rights (primarily riparian water rights). However, scarcity throughout the watershed, especially during an extended drought, may affect Delta farmers through reduced Delta water quality that increases salinity levels in Delta water beyond the tolerance of irrigated crops. The changing climate will pressure not only our existing physical infrastructure, but the statutory and regulatory infrastructure adapted to historic climate and weather patterns. For additional research and regulations on the unique water rights and usage of Delta water users, please see reports published by the Office of the Delta Watermaster of the State Water Resources Control Board (SWRCB 2020).

Farming on Delta islands is not limited by water availability because islands are surrounded by water and many are intensely subsided. Land that is below sea level requires water to be regularly pumped off to avoid saturation from damaging roots of some perennial crops, such as orchards. Farms on the fringes of the Delta that are set back from the main channels of the Delta might be more susceptible to water shortages and employ stress irrigation in droughts. Although changing rainfall patterns in the watershed are not likely to limit in-Delta water users, rainfall in the Delta is likely to become more unpredictable and variable. Unexpected downpours may disrupt agricultural schedules or compound winter water impacts (Pathak et al. 2018). Later spring extreme precipitation events can wash away pollen on fruit trees during flowering (Ibid).

Most Delta agriculture does not have to institute stress irrigation because of the shallow groundwater, but some areas in the upslope fringes of the Delta may have to use such methods in dry years. Stress irrigation diminishes yields for many crops, although some plants have strategies to tolerate stress irrigation (hereafter referred to as drought stress) for a time, and quality of some crops may increase with stress irrigation. Drought stress impacts germination and growth rate, total vegetative growth, and reproduction. Drought-stressed growth is limited by decreased photosynthetic rates, reduced nutrient uptake and allocation efficiency, reduced water-use efficiency, and injury from a buildup of reactive oxygen species (Farooq et al. 2009, Fahad et al. 2017). As a result, stressed plants tend to have reduced leaf size and limited stem and root growth (Farooq et al. 2009). Yield response to drought depends on timing, severity, and co-occurrence with other stresses (Plaut 2003). Insects and diseases can take advantage of crops that are in a drought-stressed state (Pathak et al. 2018). Drought-tolerant plants can grow, flower, and maintain yields through adjusted physiological, molecular, and morphological processes. Some are able to increase their root-shoot ratio to uptake more water, make smaller leaves more hairy, waxy, and succulent, adjust biochemical mechanisms to maintain cell functions and improve cell water balance, or escape drought by growing in a shorter period and reproducing earlier in the season (Farooq et al. 2009).

Many Delta crops, listed below, are vulnerable to drought and water stress, but as mentioned, most land in the Delta is not limited by water availability. Delta crops that have high water demand and evapotranspiration rates include alfalfa, tomatoes, pasture, rice, and corn (Jackson et al. 2011). Alfalfa can be a relatively good perennial crop choice for drought-prone areas because it has deep roots and can go dormant over the summer, resuming growth when water becomes more available (Putnam 2015). Corn quality and yields are diminished with water stress at any time, but yields are especially vulnerable the two weeks before and after silk emergence (University of California, Davis Drought Management 2019). Any reductions to water applications can also reduce yields of processing tomatoes, but several strategies exist to cope with specific land and irrigation types (University of California, Davis Drought Management 2019). Other Delta crops that may be vulnerable to water stress include nut and fruit orchards. Most Delta orchards are in the north along the Sacramento River corridor, which more reliably maintains inflows and low salinities compared to the San Joaquin River corridor (Chaudry et al. 2020). Wine grape quality benefits from reduced water applications, but strong drought combined with elevated temperatures can reduce vegetative growth and grape yield (Kizildeniz et al. 2015). Soils that are too dry can encourage early grape maturity (Webb et al. 2012).

2.2.2.2 Multiyear Droughts, Sea Level Rise, and Salinity

Through 2100, severe multiyear droughts and significant water shortages are projected to become more common. Droughts will interact with sea level rise to expose Delta water users to more frequent and widespread salinity problems. The waterways of the Delta and eastern Suisun Marsh contain fresh water during the wet season in non-drought years. During dry or drought periods, reservoir releases are necessary to limit salinity intrusion further into the Delta. Intense droughts and water shortages force water managers to make difficult choices about how to manage very limited water supplies. Historically during these episodes, water quality regulations in the Delta have been relaxed, allowing salinity to penetrate further into the Delta to manage water within the State’s water supply system. During the 2012 to 2016 drought, some Delta farmers were forced to use lower quality water, fallow, or institute conservation measures to reduce crop damages (Durand et al. 2020).

Higher salinity leads to stunted growth due to osmotic stress or ion toxicity injury (Läuchi and Epstein 1984). Delta crops range from salt-tolerant to sensitive, with the highest acreage considered moderately sensitive (Chaudhry et al. 2020). Truck crops, corn, alfalfa, corn, melons, and squash are moderately sensitive to salt, while vineyards, fruit and nut orchards, berries, and beans are sensitive, and grains, field crops, and olives tend to be moderately tolerant (Ibid).

Episodic salinity increases are not new to Delta farmers, who already adjust irrigation methods and timing with soil type, draining conditions, and twice daily tidal changes. Soil types, water salinity, and drainage management are spatially and temporally variable in the Delta. Overall, salinity is lower in wet years compared to dry years, but salinity varies by region within the Delta more than by water year type (Chaudhry et al. 2020). Across all water year types, salinity is lower in the northern Delta than the eastern and southern regions (Ibid). Delta farmers in some parts of the Delta can limit long-term soil salinity accumulations through drainage management, (Medellín-Azuara et al. 2014). However, some Delta soils have low permeability and shallow groundwater, making soil salt accumulation a problem for some farmers, especially in the summer season (Aegerter and Leinfelder-Miles 2016). During times of poor water quality coinciding with drought, water application management can mitigate damage to crops, but the soil will require leaching to limit future crop production impacts as salts build up over time (Ibid). Leaching in the Delta is typically achieved with winter rainfall (Ibid), which become less reliable with climate change (Ibid).

By 2100, sea level at the San Francisco Golden Gate is likely to rise between 2.4 and 10 feet higher than levels measured in 2000, and diffused rises in the Delta are even more uncertain (Kopp et al. 2014, Sweet et al. 2017). Modeling for the Delta Adapts Water Supply TM shows that current regulatory water quality requirements can be met in most year types for future conditions for up to at least two feet of sea level rise. Meeting these requirements requires trade-offs with water storage and Delta exports. However, acute short-term (scale of months) increases in salinity into the Delta during droughts are likely to increase. During multiyear droughts and as sea level rises, salinity levels may change unevenly throughout the Delta, impacting yields, irrigation methods, drainage requirements, and crop choice in some regions. If future multiyear droughts are handled similarly to those of the past, repeated salinity intrusions could cause significant loss of productivity and damage to agricultural assets. Towards the end of the century, conservative flow releases to sustain demand throughout multiyear droughts may not be enough to keep ocean salinity, intensified by sea level rise, from intruding further into the Delta and degrading water supplies (Wang et al. 2018).

Through mid-century, increases in episodic salinity events or salinity variability may necessitate transitions from more salt-sensitive higher-value truck and vineyard crops to less salt-sensitive lower-value crops in some regions. Although large revenue losses are not expected through mid-century, small to moderate changes in crop productivity or operating costs could determine profitability and economic viability for some farmers. Even if salinity can be actively managed, it may increase management costs.

Modeling suggests that areas currently exposed to more salinity (particularly in the west Delta) are most vulnerable to salinity increases related to sea level rise (Medellín-Azuara et al. 2014). The western Delta currently supports more salt-tolerant and less-valuable crops (Ibid), but it is unclear if these crops can withstand salinity intrusion towards the end-of-century. A 2020 Delta Protection Commission study suggests that, regardless of water year type, Delta regions with lower growing season salinity are more likely to invest in vineyards and tree crops, and regions with higher growing season salinity tend to select moderately tolerant and tolerant crop groups (Chaudhry et al. 2020). For growers that switched crops during the study period (2009 to 2016), which included a significant multiyear drought, they favored more salt tolerant and moderately tolerant crops if water salinity had increased in their region (Ibid). Updated models for precipitation, flow, sea level rise, and water management strategies will improve predictions of salinity impacts with climate change that can help growers decide how to handle these impacts.

2.2.3 Frequency of Extreme Events

2.2.3.1 Extreme Heat Events

Extreme heat days and heat waves on top of increased seasonal averages cause yield losses due to heat stress, and by cueing early development. Heat stress reduces the rate of photosynthesis, increases respiration, and can accumulate protective but off-tasting metabolites in plant tissues, resulting in reduced plant growth and decreased quality (Pathak et al. 2018). The impact of extreme heat on yields may depend on timing, especially during germination or reproductive stages (i.e., pollination, fruit set; Medellín-Azuara et al. 2018). As a result, heat waves early in spring or summer can be more detrimental than later in summer (Jackson et al. 2011). Prematurely hot days can damage plants early in development or spur rapid bolting, which may not align with timing cues for pollinators and affect crop quality. Early heat waves cause yield decreases in corn, rice, sunflowers, and tomatoes (Jackson et al. 2011, Pathak et al. 2018). Sporadic midsummer heat waves do not appear to influence yields of these crops, but iterative summer heat waves decrease yields severely (Jackson et al. 2011).

2.2.3.2 Increased Frequency and Intensity of Extreme High Precipitation and Flood Risk

The reduction of the precipitation period, with a greater proportion of precipitation falling in the Sierras as rain (often within large atmospheric river events), and warmer temperatures will cause faster snowmelt (Dettinger 2011, DWR 2015, Rhoades et al. 2018). These factors are shifting peak runoff earlier and will increase flood risk in winter and early spring, impacting the water management system's capability to store water for later use (including maintenance of Delta water quality through longer dry spells) and flood management (DWR 2015). Delta farmers will face increasing costs associated with maintaining levees and pumping water out of subsided islands. Perennial crops, such as alfalfa, orchards, and vineyards may be most vulnerable to the brunt of winter flooding. Inundation stress reduces survival and yields through root anoxia and increased vulnerability to disease and nitrogen losses (Pathak et al. 2018). For annual crops, earlier spring flooding may ruin furrows, waterlog and deplete oxygen in soil, lose nutrients and soil to runoff, delay crop plantings, and shorten the growing season, thus reducing yields (Rosenzweig et al. 2002).

Later spring flooding can severely damage or destroy recently planted crops, and by that time it may be too late to replant (Jackson et al. 2011). Successive rainfall events on fully saturated soil may lead to additional soil erosion and nutrient loss. Conditions following flooding can greatly affect recovery; cool conditions can encourage fungal disease spread while hot conditions can cause accelerated soil drying and crusting that resists root recovery. Flooding can also incapacitate roads, irrigation structures, and other agricultural infrastructure, inhibiting farmers' ability to remediate damage to crops, grow, harvest, or undertake farming operations.

2.3 Secondary Stressors

Effects of climate change on Delta crop yields are made more complex by interactions between direct impacts on plant productivity and indirect impacts that exacerbate existing issues such as pests, weeds, disease, and increasing salinity of Delta waters.

2.3.1 Atmospheric Carbon Dioxide Concentration

Elevated CO_2 may enhance crop yields through 'fertilization' of photosynthesis, but interactions with temperature, water, and available nutrients determine overall impact on growth, and accelerated growth may be at the expense of nutrition and quality (Cavagnaro et al. 2006, Blanc and Reilly 2017). In a laboratory setting, CO_2 boosts photosynthetic and growth rates and decreases water loss from stomata, especially for C3 species such as alfalfa, wheat, and soybeans (Deryng et al. 2016). Decreased water loss from stomata in some plants may impact evaporative water requirements and therefore reduce water needed in irrigation. The carbon sequestration farming system, the valuation of the carbon that plants can store in soil, may benefit from CO_2 fertilization. Crops will not be the only plants to respond to the CO_2 fertilization effect; herbaceous weeds that compete with crops may become more intense competitors (Cavagnaro et al. 2006). However, photosynthetic rates can become acclimated via enzymatic feedbacks and is regulated by biological nitrogen fixation and nitrogen fertilizer applications (Meyerholt et al. 2016). In the future, atmospheric CO_2 will reach a saturation point for plants, and other climate change impacts will likely offset benefits from CO_2 fertilization.

Additionally, increased carbon availability without a proportionate increase in soil-based nutrients can lead to increased carbohydrate content but decreased nutritional quality, including reduced protein and mineral content, and/or increases in unpalatable secondary compounds (Taub et al. 2007, Myers et al. 2014). Shifts in nutritional quality can be attributed to reduced transpiration rates, reduced mineral uptake and changes in nutrient allocation between tissues (McGrath and Lobell 2014). Without adaptation, heat stress will likely overwhelm yield-enhancing effects of CO_2 fertilization.

2.3.2 Pests, Weeds, and Disease

Temperature influences biotic stresses such as invasive weeds, animal pests, and disease spread. Animal pests, weeds, and diseases can cause large economic losses in production. Invasive pests cost California agriculture \$3 billion annually, and nationwide invasive weeds cost \$33 billion annually in agricultural losses (Bebber et al. 2013, Cal-IPC 2019, CDFA 2019, Pimental et al. 2000). Efforts to control nuisance species may substantially increase production costs. Climate change could affect the efficacy of chemical pesticides and biocontrol methods (Cavagnaro et al. 2006). Many invasive species lack natural control mechanisms in their novel ranges, making climate a primary limiting factor in spread, establishment, and impacts (Ziska and Dukes 2011). Weather extremes, precipitation, and carbon dioxide availability can affect distribution, invasibility, and agricultural impacts of invasive weeds, pathogens, and pests. Warming temperatures are likely to contribute most to invasive range expansion and damage (Ibid).

Warming temperatures facilitate expansion of geographic ranges of weeds, pests, and diseases by increasing winter survival rates and number of degree days (degree days are conceptualized as number of days that are warm enough to positively affect pest and plant development; Cavagnaro et al. 2006, Bebber et al. 2013). There is an estimated poleward shift of crop pests and pathogens of almost 1.7 miles per year, keeping pace with climate change-driven temperature increases (Bebber et al. 2013). Warmer temperatures also increase metabolism, which may augment pathogen and insect growth rates, herbivory rates, reproduction, and number of generations per year (Yamamura and Kiritani 1998, Pathak et al. 2018). Weed proliferation and success is particularly influenced by temperature; many of the biggest nuisance weeds in North American agriculture are from warm or tropical areas and could gain more advantage in competition with crops (Ziska and Dukes 2011).

Pest pressure can interact with other effects of climate change in ways that are difficult to predict. Elevated baseline stress from water quality degradation or excessive heat can make crops more susceptible to pests and pathogens (Mattson and Haack 1987), but droughts can also limit the spread of pathogens and infection rates (Huber et al. 1999). Carbon dioxide abundance may also manifest in changes in leaf/tissue characteristics or defense compounds, thereby mediating plant-pathogen interactions in positive or negative ways (as reviewed by Ziska and Dukes 2011). Plant diseases may negate potential yield boons from carbon dioxide fertilization (Butterworth et al. 2010), but it is also possible that CO_2-fertilized plants could better tolerate infections (Ziska and Dukes 2011). Consideration of holistic agroecosystem-wide shifts and new adaptation strategies will improve Delta agricultural resistance to pests, weeds, and disease.

2.3.3 Impacts to Animal Pollinators

Climate change may also disrupt crop-pollinator interactions through spatial, temporal, and behavioral mismatches (Hegland et al. 2009). Climate-induced range shifts of crops and current mutualistic partners may occur unevenly, making some crops vulnerable as new mutualisms develop (CDFA 2013). Earlier spring warming may elicit earlier flowering time when pollinators are not yet active, although flowering and pollinators appear to generally track together with warming (Hegland et al. 2009). Air temperature also mediates pollinator behavior and interactions with flowers. For example, some bees preferentially visit cooler flowers when air temperatures are high. The capability of plants to cool their flowers may affect bee visitation (Shrestha et al. 2018). Delta fruit and nut production is especially linked to managed honeybee pollinators whose populations are already vulnerable to perturbations, while other crops rely on native pollinator communities that are redundant, diverse, and likely more resilient (CDFA 2013).

CHAPTER 3. AGRO-SOCIAL VULNERABILITY

3.1 Decision-making: Balancing Economic and Climate Change Threats

Farmer decision-making processes, financial risk, employment, and culture will be affected by climate change and climate change policies. Globally, and in California, agricultural profits are projected to decline because of climate change in the latter half of the 21st Century (Deschenes and Kolstad 2011). Farmers face significant barriers to adopting technologies to prepare for climate change in the long term, such as high start-up costs and associated risk to adopting technology (Bowman and Zilberman 2013). Current issues such as technology or equipment capacity, credit limitations, a shrinking farm labor market, and crop market demands are more pertinent constraints than the threat of long-term, climate-related factors (Ibid). As sea level rises in the Delta, the cost of pumping water out of subsided islands or raising and maintaining levees (much of which is borne by the State and Reclamation Districts) will likely increase and factor into farmer decision-making on crop type.

Today, crop choices vary from year to year and decisions are usually driven by economic factors and risk aversion. Temporary crop-switching is a relatively feasible short-term adaptation strategy that increases some farmers' resilience to a changing climate, especially with respect to water supply. However, this may not be economically feasible for some farmers or crops. Crop changes also come with challenge– farmers must learn and train workers in cultivation practices, acquire new equipment, and establish new value chain connections. Advanced irrigation practices and crop choices, diversity, and acreage allocation can be implemented in response to multiyear droughts. Conversely, farmers may also plant water-intensive perennial crops to improve expected revenues (Marston and Konar 2017). Annual-to-perennial crop switches may add revenue initially but are usually more vulnerable to future water shortages than annual crops. Additionally, the 2014 Sustainable Groundwater Management Act, which requires more sustainable groundwater use by 2042, may also limit alternative water sources during drought.

Belief in climate change and perception of the potential impacts involved influence farmer behavior and vulnerability (O'Connor et al. 1999). Willingness to adopt climate change mitigation strategies and management practices may be driven by climate change beliefs. Willingness to adapt farming practice or crop choices to climate changes, such as to water supply shortages, may be more motivated by immediate local impact concerns (Haden et al. 2012). However, most farmers believe climate change is occurring (Niles et al. 2013), but there is less agreement that it is human-caused or will significantly impact local agriculture (Prokopy et al. 2015). The psychological barrier to either climate change or its potential local impacts can reduce motivation to adopt climate adaptation strategies, especially those that are costly, challenging, or complex. Additionally, farmers may perceive climate change policy risk (how regulations adjust to or ameliorate climate change might impact agricultural activities) as more of a threat than biophysical impacts (Niles et al. 2013). A study in Yolo County suggests that farmers in the

Delta region are most concerned about regulations, cost of fuel and energy, and market volatility than environmental challenges regarding water supply reliability, flooding, heat waves, or long-term temperature changes (Jackson et al. 2011). Further research would improve understanding of the vulnerabilities in Delta agricultural decision-making with regards to climate change.

3.2 Risk-mitigating Structures and Institutional Incentives

Risk-mitigating tools, such as crop insurance and incentive programs, will affect the agricultural system's mitigation and management response to climate change. State, Federal, and local programs that address reducing agriculture's contribution to greenhouse gas emissions and agricultural vulnerability to climate change are key components of the 'Climate smart agriculture' framework (Lewis and Rudnick 2019). These publicly funded programs, which promote voluntary adaptation, may lead to increased buy-in from the agricultural community in comparison to additional regulations (Ibid). One production risk reduction tool is Federal crop insurance. Insurance premium subsidies increase farmer participation, acreage of coverage, insurance returns, and reliability of farm revenue (Yu et al. 2017, Yu and Sumner 2018). Other risk-reduction support programs include tax incentives, such as that of the California Land Conservation Act of 1965 (also referred to as the Williamson Act).

Numerous incentive programs, research and education programs, and sustainability implementation grants reduce agro-economic vulnerability to climate change. Notable State resources and current programs include the California Department of Food and Agriculture's (CDFA) Climate Smart Agriculture Program, which focuses on soil enhancement, management, and greenhouse gas emission reductions; water conservation and irrigation system improvement grants; dairy methane reduction; technical assistance grants to help farmers apply for these sub-programs, and outreach and communication of sustainability tools and workshops. CDFA also supports farmers with marketing information and assistance and would be able to assist farmers with connecting climate-friendly crop changes to a new market. The California Department of Conservation invests in agricultural projects that reduce greenhouse gas emissions through its Sustainable Agricultural Lands Investment Program. The California Air Resources Board also runs the Funding Agricultural Replacement Measures for Emission Reductions (FARMER) program to aid in the purchase of agricultural equipment with lower greenhouse gas emissions. The California Energy Commission's Food Production Investment Program and Renewable Energy for Agriculture program also incentivizes climate change mitigation by helping food processors reduce energy consumption and reduce greenhouse gas emissions.

The University of California Agriculture and Natural Resources (UC ANR) is a longtime partner of California farmers through several programs including: the UC Delta Crops Research and Extension Program, the UC Agronomy Research and Innovation Center, the UC Sustainable Agriculture Research and Education Program, and the UC Agricultural Issues Center. Through these programs, the UC develops climate-minded agricultural techniques, equipment, and strategies; improves market connections; studies food systems policy and economics; and promotes farmworker well-being and agritourism.

Federal agencies and private nonprofit organizations also support California agriculture mitigate and adapt to climate change. The U.S. Department of Agriculture (USDA) has various support programs for agricultural conservation, such as greenhouse gas emission reductions, water-use efficiency improvements, and drought adaptation. The USDA Natural Resources Conservation Service also supports farmers on-the-ground by implementing new management practices for farmers. Private and nonprofit support for climate change innovations also aids farmers. For example, the National Sustainable Agriculture Coalition's Sustainable Agriculture Research and Education program invests in farmers through direct grants and indirectly through research and education grants. Community Alliance with Family Farmers (CAFF), a nonprofit organization originally founded in Yolo County, advocates for local and statewide policies to increase resilience of food and farming systems and aids farmers through several statewide programs, such as the Climate Smart Farming program.

These programs and resources can help Delta famers reduce vulnerability to climate change, but not be utilized equitably. Larger growers with higher value crops and those with more senior water rights may have greater capacity to participate in public and private programs and implement adaptation and mitigation practices. Farmers with cultural or language barriers, or older farmers that are less connected to the agriculture information network, may be less likely to be aware of and take part in these programs.

3.3 Impacts of Climate Change on Agricultural Employment in the Delta

Agriculture in and around the Delta is a major employer and contributor to the Delta's sense of place. In 2016, Delta farms supported 12,400 local primary agriculture jobs and 3,350 local value-added processing and packaging jobs (DPC 2020). Effects echo statewide; the Delta also supports 22,800 other jobs (Ibid). 2016 crop production values were $965 million and value-added processing an additional $621 million (Ibid). Delta agricultural value and jobs are likely vulnerable to climate change and are analyzed in the Vulnerability Assessment.

A literature review by Shonkoff et al. (2011) indicates that climate change will likely impact agricultural employment in two ways:

- Potential revenue losses and reduced productivity due to an increase in the frequency and intensity of extreme weather events may result in sudden layoffs of agricultural laborers, and;
- Climate impacts, such as altered precipitation patterns, may necessitate the use of costly adaptation measures.

In the central Delta, sea level rise and high inflow events that result in levee breaches/overtopping are likely to inundate prime farmland and infrastructure more frequently, affecting agricultural jobs in the region. Extreme heat days limit the potential working hours for farm workers, thereby limiting potential income. The Delta's agricultural economy and its infrastructure are already vulnerable to existing environmental stresses, such as winter flooding and levee failure; climate change will exacerbate these stresses, requiring adaptation measures.

Climate change impacts on agricultural employment in the Delta are likely to disproportionately affect disadvantaged or vulnerable populations. Low-income people of color hold most jobs in California's agricultural sector; reductions in agricultural productivity or changes in the location of agriculture due to climate change impacts would lead these low-income laborers to lose their jobs first (Shonkoff et al. 2011). In addition to providing very low wages, these jobs often provide no health insurance (Ibid), another reason why low-income laborers are more vulnerable to, and have fewer resources to adapt to, the impacts of climate change. With reductions in agricultural productivity due to climate change, unemployment among agricultural laborers in the Delta and throughout California will likely increase (Ibid).

In addition to impacting agricultural employment within the Delta, climate change will affect agricultural-based economies dependent on Delta water exports. The Delta is a critical source of water for agriculture in the Central Valley (Lund 2016). However, climate change, along with associated impacts including floods, droughts, and increasing water demand, may reduce the reliability of Delta water supply (Ibid, also see Water Supply TM). Reduced water availability due to climate change could result in reduced crop areas and yields in California (Pathak et al. 2018); these and other climate change impacts on California agriculture would likely have the largest impact in Central Valley communities and other crop-growing communities, in which agriculture is highly concentrated and low-income Latino communities are highly prevalent (Shonkoff et al. 2011). For instance, in the San Joaquin Valley—an agriculturally dependent region—negative impacts to the farm economy exacerbate the Valley's existing socioeconomic challenges, including its high unemployment rate and areas of extreme poverty (Hanak et al. 2019).

Past impacts of reduced Delta water exports due to drought may provide insight into the future impacts of climate change and Sustainable Groundwater Management Act on the Central Valley agricultural economy. Researchers at the University of the Pacific and UC Davis estimate that, in 2009, drought and environmental pumping restrictions resulted in a loss of agricultural revenue in the San Joaquin Valley of between $342,600,000 and $368,084,000, and the loss of 5,567 to 7,434 jobs (Michael et al. 2010). In response to reduced surface water allocations for irrigation during the historic 2012 to 2016 California drought, the agricultural sector in the San Joaquin Valley coped by fallowing land, switching to higher-value crops, and increasing groundwater use (Greene 2018). Growers switched from row crops to higher-value, but more water-intensive permanent nut and fruit crops, reflecting a seemingly contradictory response to drought discussed earlier in Section 3.1. A rise in prices for high-value crops, such as almonds, tempered the financial impact of the drought on agricultural businesses; however, it is estimated that, statewide, the drought resulted in the loss of 42,800 agricultural jobs from 2014 to 2016 (Ibid).

In addition to job loss, the drought resulted in other impacts on rural communities in the San Joaquin Valley, including reductions in income, declining food and water security, and adverse health impacts (Ibid). It is important to note that agricultural adaptation strategies to cope with drought, such as shifting to less labor-intensive crops and increasing groundwater use, can increase vulnerability of farm workers (Ibid). As switches become more frequent or sudden, the consistency of agricultural labor jobs might become more volatile and decrease job security. The burden of this uncertainty and job insecurity will be disproportionally borne by low-income agricultural laborers. Identifying and quantifying specific climate change impacts on agricultural employment throughout the Delta water export area is beyond the scope of this study.

3.4 Health and Safety Impacts to Agricultural Laborers

The health and safety of outdoor agricultural workers are already at risk from environmental conditions such as extreme heat, poor air quality, and vector-borne pathogens (OPR 2017). Farm workers are at risk for heat-related illness because they are more exposed to extreme heat and are more sensitive because body temperatures are elevated during strenuous activity (Gamble et al. 2016). Between 1992 and 2006, crop workers made up 16 percent of occupational deaths in the U.S. from exposure to environmental heat (Centers for Disease Control and Prevention 2008). Despite California's strong worker protection requirements against heat-related illness, vulnerability to heat stress is still persistent because of socio-cultural behaviors and workplace structures (Courville et al. 2016). Extreme heat days are expected to become more frequent with climate change and will require modified working practices to further reduce risk of heat-related illness. Agricultural workers are also exposed to unhealthy air quality conditions such as air pollution and dust, both of which may increase with rising temperatures. Climate change is projected to increase wildfire frequency and severity in areas surrounding the Delta (Westerling and Bryant 2006), which can create hazardous air quality conditions downwind, affecting outdoor agricultural laborers. Warming temperatures may also shift pathogen distributions, disproportionately affecting outdoor workers such as farm laborers (UC Davis Western Center for Agricultural Health and Safety). Workers living in temporary housing shelters may additionally be exposed to these conditions outside of working hours, amplifying exposure risk. Climate change will likely worsen these conditions and intensify health inequities.

Figure 4: Outdoor agricultural workers will be impacted by climate change

CHAPTER 4. KEY FINDINGS

4.1 Impacts on Crop Yields

The key findings for prominent crops currently grown in the Delta are reported by climate stressor and/or hazard as outlined in 2.1.

Temperature: Delta crop yields will respond both positively and negatively to warming temperatures and longer summers due to climate change. Warmer temperatures may benefit yields of alfalfa, melons, citrus, olives, tomatoes, and sweet potatoes, but negatively affect fruit and nut crops. Increasing winter temperatures and continuing decline of days with enough chill and fog will negatively impact high-value fruit and nut trees.

Precipitation and Sea Level Rise: While water availability will not be the limiting factor for Delta farmers with senior water rights, water quality could be. Higher irrigation salinity conditions in the Delta are expected during episodic droughts and will be exacerbated by sea level rise (Delta Adapts Water Supply TM). If higher salinity conditions become more frequent or more widespread over time, less-valuable but more salt-tolerant plants may be favored and affect overall Delta yields and profits.

Extremes: Extreme heat days on top of increased average temperatures can lead to crop losses due to heat stress, water stress, and early development effects. Perennial crops, such as alfalfa, orchards, and vineyards may be most vulnerable to prolonged and increased winter flooding, and annual crop planting may be delayed because of soil waterlogging.

Secondary Factors: Increased atmospheric carbon dioxide may initially boost plant growth but decrease crop nutritional quality over time and increase competition with weeds. Novel pests and diseases or increased pressure from existing ones may become more difficult to manage.

4.2 Governance, Policy, and Social Vulnerability

Climate change policy, risk communication, institutional incentives, and support programs can reduce agricultural production vulnerability. Agricultural labor is likely to lose jobs from reduced production and risk of flooding and be exposed to increased health hazards from heat and air quality. Vulnerable populations and socially disadvantaged farmers are likely to be the most affected. Climate change, along with associated impacts including floods, droughts, and increasing water demand, may reduce the reliability of Delta water supply exported to south-of-Delta agricultural water users.

CHAPTER 5. KNOWLEDGE GAPS

5.1 Data and Knowledge Gaps

In addition to the Delta Protection Commission's recent studies (Fairbanks et al. 2019, Chaudhry et al. 2020), additional research on agricultural challenges by sub-regions of the Delta will benefit regional adaptation strategies. Crop impacts or switches, as well as adaptation strategies, may be more appropriate for one sub-region over another.

Ecological research suggests that the Delta may be a climate or thermal refuge for species in the context of the Central Valley. Likewise, additional agricultural research will determine if the Delta could serve as a refuge for some crops in comparison to the Central Valley.

Another prominent data gap is public identification of specific drought- and heat-tolerant crop varieties that would be successful under the expected conditions in the Delta under climate change. Some growers are already trying to anticipate future conditions with privately developed climate change-resistant varieties and thus be less vulnerable than the conclusions of this literature review suggest.

There are additional knowledge gaps around farmer perception of climate change risks, willingness and interest to engage with potential adaptation and mitigation strategies at the individual and institutional level, and resulting behaviors and decision-making.

5.2 Science, Policy, and Management Questions

1. What are the biophysical impacts to agricultural yields in the Delta?
    a. Specifically, how will increasing air temperatures and changing precipitation patterns affect agricultural yields in the Delta?
    b. How will flooding, water quality degradation, and salinity affect agricultural yields in the Delta?
2. How might cropping patterns change under climate change?
3. What institutional support structures (incentives, insurance, consultants, extension programs) are needed to support the agricultural community to become a climate-resilient sector?
4. How can Federal, State, and local policies be coordinated to promote synergistic goals for agriculture that also address expected climate vulnerabilities?

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