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UNIVERSITY OF CALIFORNIA, MERCED

CLIMATE SUITABILITY AND AGRONOMIC INTEGRATION OF HIGH-
VALUE SPECIALTY CROPS IN CALIFORNIA:
COFFEE, OLIVES, AND SAFFRON AS MODELS FOR CLIMATE-RESILIENT
DIVERSIFICATION

DISSERTATION

submitted in partial satisfaction of the requirements

for the degree of

DOCTOR OF PHILOSOPHY

In Management of Complex Systems

by

KENNETH B. PREWITT

Dissertation Committee:

PROFESSOR JOHN ABATZOGLOU, ADVISOR, CHAIR

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December 2025

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The dissertation of Kenneth Prewitt, titled Climate suitability and agronomic integration of high-value specialty crops in California: coffee, olives, and saffron as models for climate-resilient diversification is approved:

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ABSTRACT OF THE DISSERTATION

Climate suitability and agronomic integration of high-value specialty crops in California:
coffee, olives, and saffron as models for climate-resilient diversification

by

Kenneth Burrell Prewitt

Doctor of Philosophy in Management of Complex Systems

University of California, Merced, 2025

Professor John Abatzoglou, Chair

California's agricultural systems face dual pressures of water scarcity and climate variability intensified by the Sustainable Groundwater Management Act (SGMA). This dissertation integrates spatial modeling, climate analysis, and agronomic feasibility assessments to evaluate three high-value specialty crops — coffee, olives, and saffron — as models for sustainable diversification in the San Joaquin Valley and other water-limited regions. Using high-resolution historical and future climate data, thermal suitability thresholds were mapped and coupled with floodplain and irrigation demand models to define zones of opportunity and constraint. The results show that coffee can be cultivated in coastal and foothill microclimates, olives provide a water-smart alternative to tree nuts, and saffron offers ultra-low water use and seasonal dormancy aligned with SGMA objectives. Collectively, these findings demonstrate how data-driven crop substitution and system optimization can reduce water use while maintaining economic viability, supporting California's transition to climate-resilient agriculture.

Chapter 1. Introduction, Motivation of the Dissertation

If California were a sovereign nation, it would hold the fifth position globally in terms of total Gross Domestic Product (GDP), amounting to approximately \$4.215 trillion in the second quarter of 2025 (United States Government, 2025; Bohn & Duan, 2025). Despite the state's diverse economy, the agriculture sector contributes a modest 2.5 percent—equivalent to \$85 billion—to the overall state economy as of 2021. This includes approximately \$51.3 billion in cash receipts and \$33.7 billion in farm value-added services (CDFA, 2023; USDA, 2024). The Gross Production Value of California's total agriculture production would rank fifth worldwide, following China, the United States, India, and the Russian Federation, accounting for about two percent of the global agricultural economy.

The strength of California's agricultural economy lies in its ability to produce numerous high-value specialty crops that are less suitable in other regions of the United States. California provides more than 400 commodities, which make up approximately 75 percent of the nation's fruit and nut production (CDFA, 2023). Table 1 illustrates the diversity of crops in which California leads the nation in production. Fruits and nuts are classified as "specialty crops," defined as fruits and vegetables, tree nuts, dried fruits, horticulture, and nursery crops (including floriculture) as part of the Specialty Crops Competitiveness Act of 2004 (P.L. 108-465, 7 U.S.C. 1621 note). Examples of specialty crops widely grown in California include almonds, pistachios, and grapes, which together contribute roughly \$22.2 billion annually—approximately 44 percent of the state's agricultural economy (CDFA, 2022).

The San Joaquin Valley (SJV) alone accounts for approximately \$37 billion in annual agricultural production value in 2022, comprising over half of California's total agricultural output and roughly 5.7% of the entire U.S. market (USDA NASS 2023). Widespread high-value specialty crops (e.g., including almonds, pistachios, grapes) and dairy are leading economic drivers of the regions agricultural economic. While only 2.5% of the state's GDP is derived from agriculture, the sector accounts for 16.4% of the SJV's gross domestic product (US BEA 2025) and supports about half of the state's agricultural workforce (CA Employment Development Department 2025).

Table 1.1. Major Specialty Crops Produced in California (2023–2024)

Rank	Crop	2024 California Value (USD Billion)	% of U.S. Production	U.S. Share of World Production (%) / Rank	Notes and Context
1	Almonds	5.66	≈ 100	≈ 80 / #1 worldwide	California dominates global almond markets; key export crop
2	Grapes (all uses)	5.64	≈ 99	— (top 5 globally)	Largest U.S. source of table and wine grapes
3	Lettuce	3.67	≈ 70–75	U.S. #2 after China	CA and AZ dominate
4	Strawberries	3.46	≈ 89–90	U.S. #2 after China	Nearly all berries come from coastal California.
5	Pistachios	2.05	≈ 99	≈ 45 / #1 worldwide	Nearly exclusive to CA.
6	Tomatoes (processing + fresh)	1.64	≈ 95	Top three globally	Major processed-food and export commodity.
7	Carrots	1.57	≈ 85–90	Top five globally	CA’s sandy soils favor high-quality production.
8	Walnuts	1.04	> 99	≈ 50 of world trade / #2 after China	Extensive Central Valley orchards.

9	Mandarins / Tangerines	1.00	≈ 97.5	— (top five globally)	Fast-growing citrus segment in CA’s southern valleys.
10	Broccoli	0.98	≈ 89	Top three globally	CA remains near- monopoly U.S. supplier.

Sources: California Department of Food and Agriculture (2024); USDA NASS (2024); FAOSTAT (2024);

Each specialty crop exhibits distinct climatic and hydrological requirements. California’s Central Valley – the southern half of which is the SJV – encompasses approximately 20,000 square miles and is one of the world’s most productive agricultural regions. This region provides most of the state’s almonds, walnuts, pistachios, and olives, as well as grapes for both table and wine production. Coastal counties—Monterey, Ventura, Santa Barbara, San Luis Obispo, and Riverside—produce artichokes, celery, strawberries, and spinach. This diversity of production reflects the range of microclimates across the state, each shaped by temperature, precipitation, and soil conditions.

However, climate change—through both rising temperatures and more insecure water supply—threatens this dynamic. Absent adaptation efforts, such changes could significantly restrain cultivation, reduce yield, and increase production costs (Therios, 2009). Warmer winters can lead to insufficient chilling hours for stone fruit and nut crops. Because specialty crops dominate local economies, reduced viability directly affects rural employment and regional economic stability. This is particularly true in the SJV – given the significant reliance on agricultural economies for jobs.

Where irrigation is limiting, groundwater extraction has historically compensated for water deficits. In 2014, the California State Legislature enacted the Sustainable Groundwater Management Act (SGMA) to address declining aquifer levels and related impacts. SGMA aims to prevent significant and unreasonable declines in groundwater levels, storage depletion, land subsidence, and surface-water depletion. Functionally, SGMA serves as the “situation paragraph” of California’s agricultural operations order—it defines the terrain, actors, and operational constraints under which growers must adapt. It establishes the boundaries within which new strategies, such as diversification and repurposing, must operate.

Studies estimate that under SGMA, without new water supplies, approximately 900,000 acres of farmland could be fallowed, resulting in 50,000 lost jobs and a 2.3 percent

regional economic decline (Hanak et al., 2023). The Public Policy Institute of California (PPIC) identifies five potential responses for agricultural lands in light of SGMA: (1) crop substitution, (2) solar energy expansion, (3) fallowing of marginal lands, (4) real estate development, and (5) habitat restoration. Of these, land repurposing—especially toward climate-resilient, high-value specialty crops—offers the greatest potential for balancing environmental sustainability with economic viability.

Repurposing success depends on identifying climate-smart crops that align with California’s evolving climate: resilient to heat and water scarcity while maintaining high market value. Such crops must also meet quality and traceability standards consistent with international trade expectations (e.g., ISO, professional societies). Selection should optimize environmental, economic, and social benefits within SGMA’s policy framework.

This dissertation evaluates three specialty crops: coffee (*Coffea arabica*), olives (*Olea europaea*), and saffron (*Crocus sativus*). Each crop exhibits favorable traits for adaptation—defined market value, resilience to climatic stressors, and established international production standards. Coffee offers novelty and emerging niche potential within California’s coastal regions. Olives represent a proven, drought-resilient perennial suited to micro-irrigation and deficit-irrigation systems that while grown in California, could be more widely distributed. Saffron exemplifies extreme water-use efficiency and high economic return, with irrigation requirements as low as 260 millimeters annually during its growth phase. Collectively, these crops reflect a strategic spectrum: coffee as climatic-frontier innovation, olives as perennial efficiency, and saffron as micro-scale high-value specialization.

The purpose of this dissertation is to identify areas within California suitable for cultivating these crops under current and near-term climate conditions. Using geospatial and multi-criteria decision frameworks, I assess thermal, hydrological, and economic suitability to inform grower adaptation and policy decisions. The overarching research question is: how can California sustain agricultural productivity and economic viability under both climate change and SGMA-driven water constraints?

In Section II, I highlight coffee suitability under both current and near-term climate conditions, guided by previous studies on perennial crop modeling (Parker & Abatzoglou, 2017). Section III focuses on olives, addressing climatic and hydrological suitability and their potential as replacements for more water-intensive crops like almonds. Section IV presents a research prospectus for saffron cultivation, including phenological advantages and intercropping opportunities. Together, these analyses provide a framework for climate-resilient crop diversification in California.

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CHAPTER 2. CLASSIFYING CLIMATE-SUITABLE LANDS IN CALIFORNIA FOR COFFEE CULTIVATION¹

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2.1. Abstract

Specialty coffee markets have grown in recent decades. Given increased market and climate volatility in coffee-growing regions of the world, there is interest in cultivating coffee outside of the tropics, including in California. While several small coffee farms have established in the state over the past decade, no studies have identified and quantified climatically suitable regions for growing coffee. We developed a model of *C. arabica* suitability based on agronomic studies of thermal constraints to coffee cultivation, combining heat and cold intolerance with energy requirements for maturation. This model was applied to agricultural lands across California using high-resolution climate datasets for both modern (1991–2020) and projected near-term (2021–2050) conditions. We explored the potential for moderating influences of farm management approaches for thermal extremes – such as using agroforestry shade trees – to augment thermal suitability. Results indicate that, in the absence of thermal management approaches, nearly all agricultural lands in the state experience temperature extremes in the modern climate that are detrimental to coffee cultivation. By contrast, we found that over 230 km² of agricultural land in coastal southern and central California is thermally suitable for coffee with management efforts. These suitable areas include most of the state’s avocado cultivation – which may serve as a thermal buffer for coffee and favor the environmental and economic agricultural sustainability of this coupled crop system. We additionally show that projected near-term climate leads to moderate increases in thermally suitable agricultural land for coffee to over 350 km² coupled with management efforts. Despite numerous economic and logistical challenges, that impede the growth of a burgeoning coffee region in coastal, southern, and central California, we demonstrate that climate conditions in both the present and the future, combined with agronomic management efforts such as shading, provide an opportunity for a viable coffee production in California.

2.2. Introduction

Coffee is among the most traded commodities globally and of critical economic importance to approximately 25 million small farmers worldwide engaged in coffee operations (Ovalle-Rivera *et al.*, 2015). Almost all the world’s coffee is grown in 60 countries located in the tropics (Santana *et al.*, 2021). Arabic coffee (*C. arabica*) makes up approximately 60% of the entire market share of coffee, comprises most of the specialty coffee globally, and is thus of vast importance to export markets for these

¹ This chapter contains material previously published as Prewitt *et al.* (2025) in the *International Journal of Climatology*. <https://doi.org/10.1002/joc.8678>

countries (Wintgens, 2004). Increased global demand for coffee including specialty coffees has occurred in recent decades (Lyons, 2005; Urwin *et al.*, 2019; Koutouleas, *et al.*, 2022). However, many coffee cultivation regions have increased environmental challenges including climate change that impacts both crop yields and quality (Moat *et al.*, 2017; Tavares *et al.*, 2018). An adaptation mechanism to sustain production of high-quality coffee in a warming climate is the upward vertical migration (i.e., altitude) of cultivation to cooler locations in the mountainous regions where coffee is currently grown (Jawo, Kyereh and Lojka, 2023). There is also interest in identifying areas suitable for high-quality coffee cultivation at higher latitudes outside the tropics (Zullo Jr *et al.*, 2011). This interest in latitudinal migration has resulted in new geographic entities entering the coffee market, including the recent cultivation in the southern and central coast regions in California. Although novel to this area, commercial cultivation of coffee occurs in other US states and territories including Hawaii and Puerto Rico.

Much of the global coffee crop is grown in the tropics where annual mean temperature is between 18-22°C (Wintgens, 2004). Coffee, specifically *C. arabica*, is intolerant to both extreme heat and freezing temperatures. Further, coffee requires sufficient energy accumulating for cherry maturation, thereby imposing additional environmental constraints on thermal crop suitability. In sub-optimal climates, cultivation and management avoiding microclimates prone to cold air drainage, as well as using shading to buffer the impacts of high temperatures are practiced (Wintgens, 2004). Most of the literature on climate and weather suitability for coffee cultivation, *C. arabica*, is from the tropics where temperature regulation occurs due to elevational regulation and interaction (Zullo Jr *et al.*, 2011).

Specialty crops are of vital importance to California's agricultural economy, generating cash receipts more than sixteen billion dollars that account over 28% of the state's direct agricultural value (USDA, 2023a; United States Department of Agriculture, 2023). Coffee is not among the specialty crop acreage grown in sizable numbers in the state, yet California does have a history of coffee growing and marketing. Historically, there are records of unsuccessful attempts to grow coffee in California in the 19th century due to freeze events (Steward, 1964). In the 1970s, the state's affiliation with specialty coffee was initiated through the founding of key coffee businesses such as Pete's and Hills Brothers. This branding of high-quality coffee was geared toward a premium market that contributed to the increased global demand for high-quality specialty coffees which focus on quality and geography (Wheeler, 2001; Borrella, Mataix and Carrasco-Gallego, 2015).

In the past two decades, several small coffee farms have established in southwestern California, leading to growing interest in developing a specialty market for locally grown California coffee. Further development of coffee suitability included the identification of specific and more suitable microclimates, such as in the greater Santa Barbara region initiated by Mark Gaskell Ph.D., and Jay Ruskey (Ruskey, 2021; Myers, 2023). Thus, the cultivation of coffee can occur in parts of the state, although no known efforts to identify and quantify climate suitability across the state has been undertaken.

This study examines the present and future climate suitability of *C. arabica* cultivation in California. Numerous studies have examined contemporary and future climate suitability

of agricultural crops using various approaches (Fraga *et al.*, 2016; Fain *et al.*, 2018; Omazić *et al.*, 2020). We review the scientific literature on climate suitability of coffee, assemble high-resolution climate datasets, and create spatial models for coffee cultivation suitability. We additionally examine how coffee growing suitability can be augmented with on-farm management approaches such as crop shading that buffer temperature extremes. Moreover, given planning horizons for coffee growing and ongoing climate change, we evaluate how thermal suitability for coffee is projected to change in the coming decades in California.

2.3. Methods

We developed a conceptual model to identify suitable areas for coffee cultivation focusing exclusively on thermal suitability. This model focused exclusively on thermal constraints and ignored precipitation, as much of California’s agriculture relies on supplemental irrigation to meet crop water demands. This modeling approach follows that of previous studies for specialty crops that considers both biophysical-based temperature thresholds detrimental to yield over the crop phenological cycle, as well as to energy requirements for maturation (Parker and Abatzoglou, 2017; Abatzoglou, J. T. 2013). We focus on thermal factors as temperature is often the most crucial factor influencing plant growth and development. Our model was parameterized by numerous studies that have examined the influence of temperature on coffee plant physiology and coffee quality (Wintgens, 2004; Pezzopane *et al.*, 2008). We focused on three primary thermal requirements for the suitability of coffee cultivation: (i) cold intolerance, (ii) heat intolerance, and (iii) energy requirement for coffee cherry maturation (Table 1). Suitability is a product of all three requirements. If any of the three thermal conditions are not met in a growing year, the crop may become unviable resulting in significant financial and management concerns for the producer. Moreover, we focus on the thermal suitability over 30-year time horizons, which entrains the influence of interannual climate variability and extremes in the metrics. This approach is preferable to using 30-year averages as inputs, particularly for longer-lived perennials.

Biophysical process	Threshold	Reference
Frost damage	0°C	DaMatta & Ramalho, 2006; Wintgens, 2012
Heat damage	35°C	DaMatta & Ramalho, 2006; Rising, 2016
Thermal accumulation for maturation	2778°C	Pezzopane, et al., 2008

Table 2.1: Thermal requirements and thresholds used in the coffee thermal suitability model. A base 10.2°C threshold is used to calculate growing degree days between April and August in the subsequent year. The thermal management approach further assumes 3°C buffering of cold extremes and 6°C buffering of heat extremes.

Cold temperatures can result in significant or even catastrophic effects on coffee's metabolic capability as well as negatively affect the coffee quality, annual production, and marketability (Pezzopane *et al.*, 2008). Coffee plants can withstand temperatures at or near 2°C, but are generally intolerant of temperatures below 0°C which can result in moderate frost damage (Wintgens, 2004). It may take up to 24 months for plant recovery following frost-related damages resulting in longer-term ramifications for cold exposure beyond the current growing season (DaMatta and Ramalho, 2006; de Oliveira, Alves and Vitória, 2009; Rising, 2016). This study used 0°C as a threshold for cold intolerance.

Similarly, extreme heat also impacts coffee plants. For example, at temperatures exceeding 30°C coffee plants show reduced photosynthesis efficiency and cellular damage (Kuit, Jansen and Van Thiet, 2004; DaMatta *et al.*, 2018). Prolonged exposure to temperatures above 35°C can accelerate a decline in tree health (Drinnan and Menzel, 1995; DaMatta and Ramalho, 2006) and result in lower quality product that is unsuitable for the specialty market (Wintgens, 2004; Rising, 2016). We used 35°C as a threshold for heat intolerance.

The maturation (flowering to harvest) of the arabica coffee cherry is around 6-9 months in the tropics (Wintgens, 2004; Pezzopane *et al.*, 2008). In California, growers have instead found that cherries mature over the course of an entire year, which has been described as “super-slow cherry development”, with flowering during March to April and harvest of those coffee cherries occurring the subsequent year from May until September (Myers, 2023). This difference in maturation time from traditional growing areas to non-traditional regions at different latitudes is seen in other crops (Hamze a, , Trentacoste, Searles, & Rousseaux, 2022). The energy requirements for cherry maturation have been well studied in tropical climates and estimated at approximately 2887°C (base temperature of 10.2°C growing degree days) between flowering and harvest (Pezzopane *et al.*, 2008). To account for the longer maturation period of cherry development in California, we calculated growing degree days (GDD) between 1 April and 31 August the subsequent year (518 days, equation 1), where T_{mean} is the daily average temperature.

$$GDD = \sum_{i=1}^{518} \max(T_{mean} - 10.20) \quad (1)$$

We used gridded daily maximum and minimum temperature data from gridMET (Abatzoglou, 2013) covering the 1991-2020 period. gridMET is a daily surface meteorological dataset that blends attributes reanalysis and station observations to create a ~4-km (1/24°) horizontal resolution dataset. The 4-km horizontal resolution grid captures temperatures at landscape scales but may not capture site-specific microclimates at sub-kilometer scales such as those associated with cold air drainage or vegetation canopy effects (Lundquist, Pepin and Rochford, 2008; Davis *et al.*, 2019). While these data cover the contiguous US, we constrained our analysis to within the state of California. Future climate projections from 20 climate models participating in the Sixth Coupled Model Intercomparison Project were incorporated to provide an estimate of the projected changes in temperature for the coming decades (Gutiérrez, Jones and Narisma, 2021). For simplicity, we calculated the multi-modeled change in mean annual

temperature between 2021-2050 and 1991-2020 across California for a moderate mitigation pathway (SSP2-45). The result is approximately 1°C (Fig. 1b) with the amount of warming across models generally scaling with magnitude of warming in global mean temperature (Fig. 1c). Hence, for the future 2021-2050 period we superposed a 1°C uniform warming to the daily gridMET data during 1991-2020. By using a sensitivity analysis, we have a seamless comparison between the modern 1991-2020 period and future 2021-2050 period.

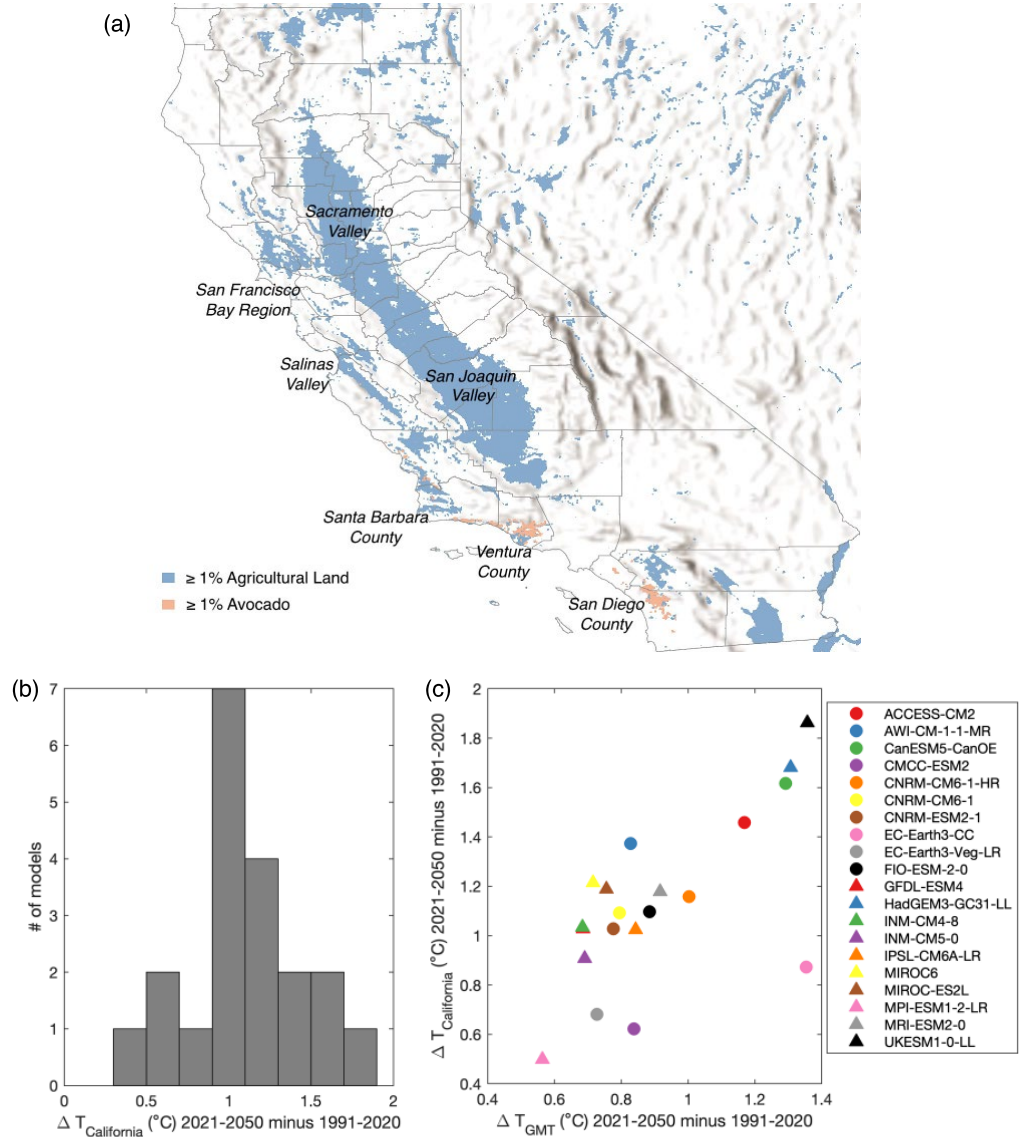


Figure 2.1 (a) Map of study area showing currently cultivated land in California ($\geq 1\%$ land cover in agriculture, blue) and locations where avocado are cultivated ($\geq 1\%$ land cover, peach). (b) Distribution of projected changes in annual mean temperature averaged over California between 2021-2050 versus 1991-2020 from 20 CMIP6 models. (c) Relationship between changes in annual global mean temperature and annual mean temperature over California across the 20 CMIP6 models.

Following Parker and Abatzoglou (2017), we applied our thermal suitability model, which queries whether a location has sufficient thermal accumulation and avoids both cold and heat extremes that are detrimental to production each year. The model was run over a 30-year period for the modern (1991-2020) and future (2021-2050) period, capturing the climate risks that accounts for interannual climate variability on crop suitability – given the multidecadal lifetimes of coffee plants. We calculated the percentage of years that have suitable conditions favorable for all three criteria, as well as the percentage of years meeting individual criteria to identify how different thermal factors constrain crop suitability. We defined a locale to be suitable where overall suitability exceeds 80% (i.e., at least 8 of 10 years being successful from a thermal perspective), based in previous studies that have examined risk tolerance of perennial crop systems (Parker and Abatzoglou, 2017). Lastly, we limited our analysis to land areas presently in agriculture or cultivated lands as defined by US Department of Agriculture National Agriculture Statistics Service (USDA-NASS) 30-m Cropland Data Layer during 2012-2022 (USDA, 2023b). The Cropland Data Layer is derived from remotely sensed data, is widely used for agricultural land classification in the US and has an overall accuracy of exceeding 80% in California (USDA, 2023b). While the classification accuracy in California can be reduced due to the high number specialty crops, the footprint of cropped acreage is highly reliable (Espinoza, Booth, & Viers, 2023). We aggregated the Cropland Data Layer to a 1-km resolution grid. Suitability was examined for grid cells with at least 1% agricultural coverage (Fig. 1a). We used a nearest neighbor interpolation to project the 4-km gridMET meteorological data to the 1-km resolution agricultural land dataset for further analyses.

We conducted two sets of runs for both contemporary and future climate conditions. First, we used the set of thermal requirements from Table 1, which assumes no management strategies to moderate heat and cold extremes. Second, we examined how the climate suitability of coffee is augmented with agronomic management strategies that can be implemented to buffer temperature extremes. A strategy of particular interest and suitability to the region is the employment of agroforestry shade tree cultivation (Koutouleas *et al.*, 2022). Shade trees are used throughout the tropics in part for their multi-cropping benefit to smallholder farmers (Perfecto *et al.*, 1996). In the California context, the avocado (*Persea americana*) tree is an ideal shade candidate because it co-exists within the coffee microclimate niche with similar temperature and soil requirements, although many avocado cultivars can generally tolerate temperatures a few degrees cooler than the absolute limits for coffee and are more heat tolerant (Grüter *et al.*, 2022). The implementation of the shade tree strategy has a temperature buffering effect on the understory crop. This can increase cold temperature extremes by 2-4°C and decrease hot temperatures extremes by 5-6°C (Lin, 2007; Koutouleas *et al.*, 2022). Our thermal management modeling scenario therefore uses a higher maximum temperature extreme (41°C, or 6°C above the non-managed upper threshold) and lower minimum temperature extreme (-3°C, or 3°C below the non-managed upper threshold) accounting for this buffering effect. We additionally note that other agronomic management

approaches, such as the use of wind machines and irrigation, can also be used to moderate heat and cold impacts.

There is no means to validate our thermal suitability model for coffee given the limited cultivation in California to date and thus the lack of a publicly available geodatabase of coffee farms locations. Rather, we conducted a pseudo-validation of coffee thermal suitability with 2019 Cropland Data Layer data where at least 1% of agricultural land was classified as avocado. Avocados are a more mature specialty crop in California, and avocado trees are being used as overstory crops with coffee as an understory crop in agroforestry locations worldwide (Megerssa and Alemu, 2013; Grüter *et al.*, 2022). Hence, the pseudo-validation was conducted using contemporary climate with the thermal management strategy. We specifically quantified both the mean thermal suitability at lands where avocado is grown and the percent of such lands where suitability exceeds 80%. These statistics were also computed for all croplands for a comparative analysis.

2.4. Results

Thermal suitability for coffee under modern climate without application of thermal management approaches showed very poor overall suitability (<20% of years suitable) across the state, with a few pockets of moderate overall suitability (>60%) in coastal and near-coastal agricultural lands of southern California including Santa Barbara, Ventura, and San Diego counties (Fig. 2a). Most growing areas met suitability requirements for energy requirements except for coastal agricultural areas in central California (Fig. 2b); however, most of these areas frequently had temperature extremes beyond the established limits for high-quality coffee production (Figs. 2c-d). Cold intolerance was particularly prevalent within the state with only coastal and near coastal agricultural lands in central and southern California having $\geq 80\%$ suitability for cold (Fig. 2d). Paradoxically, some of these near coastal environments that had high suitability for cold intolerance had insufficient energy requirements met due to the persistent cool maritime conditions during the growing season.

By contrast, we find that coffee suitability is more suitable across isolated pockets of coastal agricultural land in southern and central coastal California under modern climate with the adoption of thermal management strategies (Fig. 3a). This occurs due to a combination of management approaches that mitigate extreme effects of both heat and cold given the thermal intolerance of coffee (Fig. 3c, 3d). Notably, we show an expansion in locations with overall suitability $\geq 80\%$ to 236 km² of cultivated lands with thermal management. This includes most of the geography encompassing the limited sample of experimental coffee farms in south coastal California. In addition, model results show potentially suitable growing areas near the San Francisco Bay Area, albeit small in area. The large agricultural regions of the Sacramento and San Joaquin Valley is unsuitable, as its climate is too harsh and management strategies would not be able to mitigate effects of extreme temperatures. In the near coastal agricultural lands of central and southern California, we show a set of thermal constraints for coffee across a thermal gradient. For

maritime climates, overall energy requirements (i.e., growing degree days) are limiting in locations such as the Salinas Valley. Whereas further inland, a combination of hot and cold extremes limits overall suitability even with management efforts.

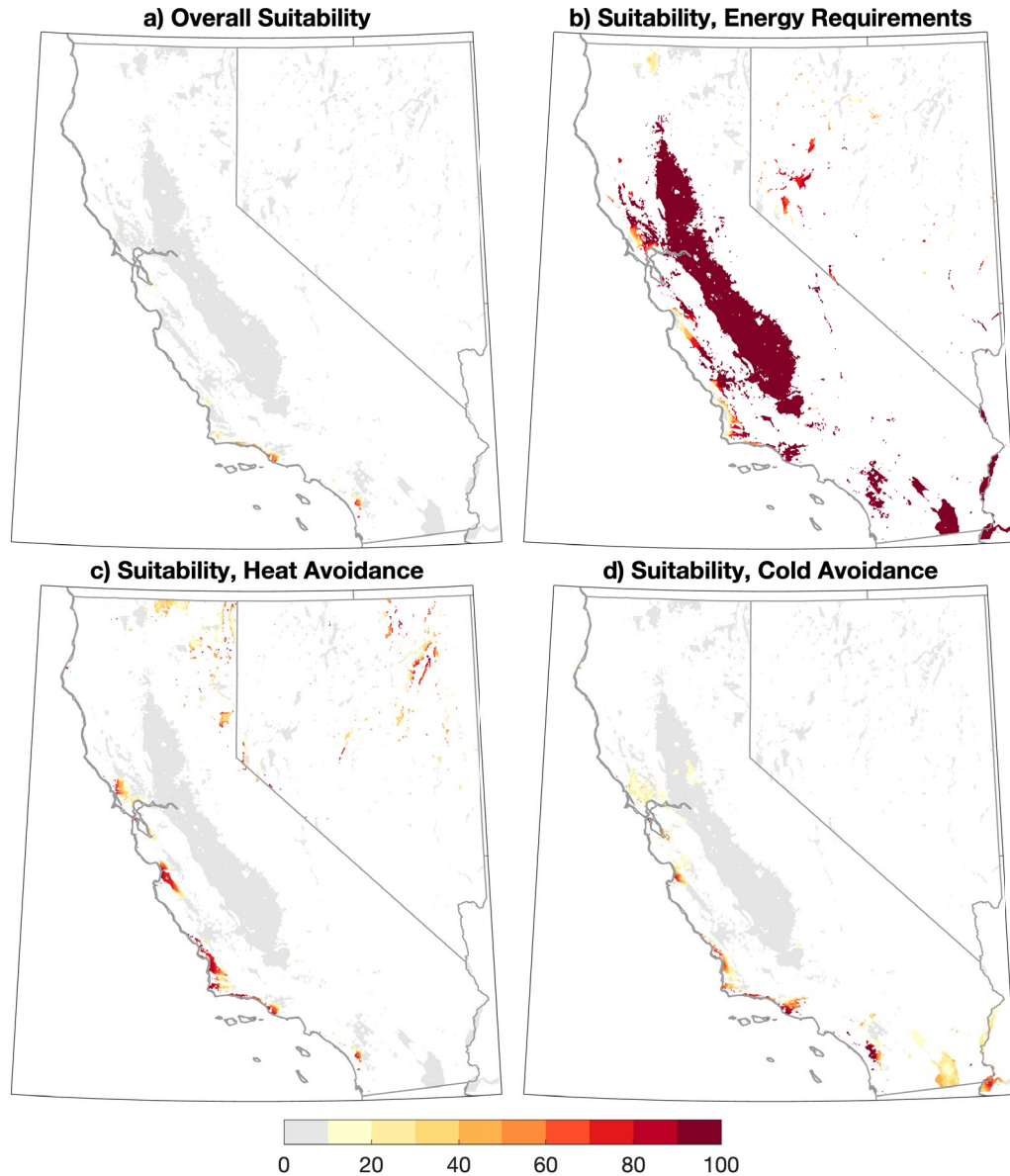


Figure 2.2: Thermal suitability for coffee based on modern climate of 1991-2020. Results are shown for (a) overall thermal suitability, (b) energy requirement suitability, (c) heat avoidance suitability, and (d) cold avoidance suitability. Scores are shown on a scale from 0 (no years suitable) to 100 (all years suitable) and non-cultivated lands are masked out in white.

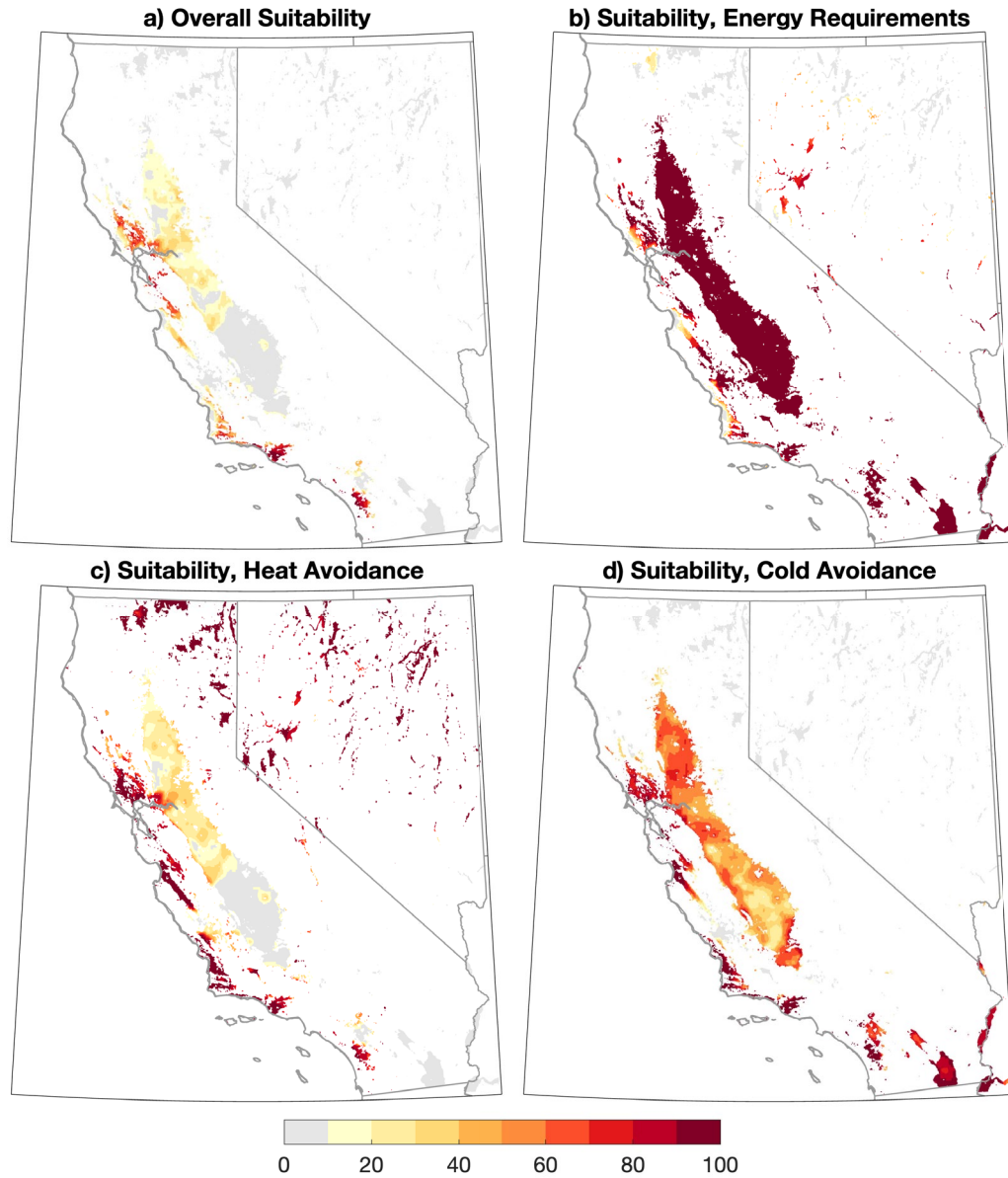


Figure 2.3: Thermal suitability for coffee based on modern climate of 1991-2020 incorporating thermal management. Results are shown for (a) overall thermal suitability, (b) energy requirement suitability, (c) heat avoidance suitability, and (d) cold avoidance suitability. Scores are shown on a scale from 0 (no years suitable) to 100 (all years suitable) and non-cultivated lands are masked out in white.

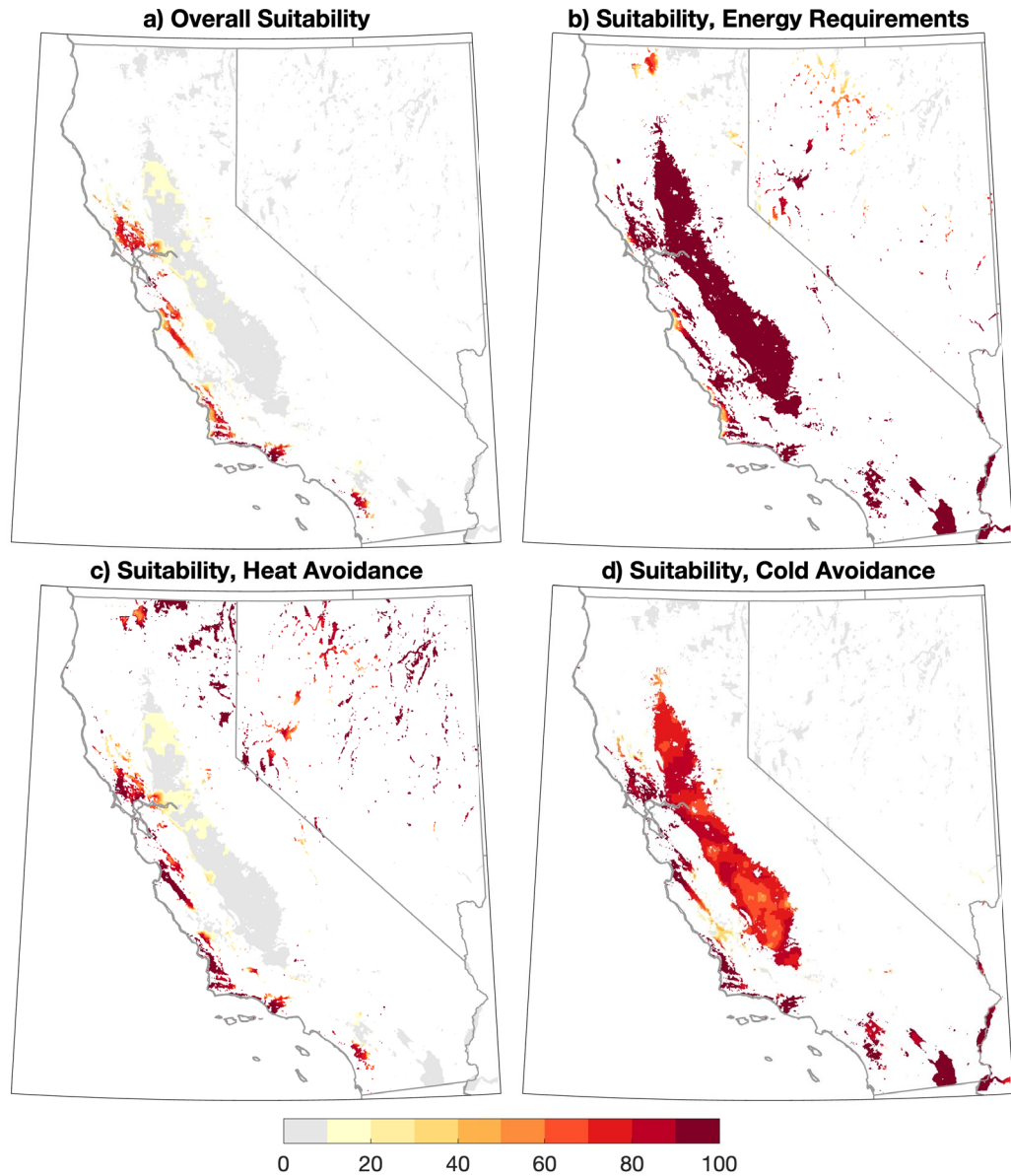


Figure 2.4: Thermal suitability for coffee based on future climate of 2021-2050 incorporating thermal management. Results are shown for (a) overall thermal suitability, (b) energy requirement suitability, (c) heat avoidance suitability, and (d) cold avoidance suitability. Scores are shown on a scale from 0 (no years suitable) to 100 (all years suitable) and non-cultivated lands are masked out.

Given the increased thermal suitability for coffee achieved through both management strategies and the common practice of growing avocado or similar shade trees above coffee, we prioritized validating our model using data based on modern climate with thermal mitigation techniques. Approximately 1.9% of agricultural lands in the state had suitability $\geq 80\%$, with a mean suitability across all croplands of 15.1% (Fig. 3). By contrast, for locations with avocados per the 2019 Cropland Data Layer (Fig. 1a), 65% of lands had suitability $\geq 80\%$, with a mean suitability across croplands with avocado of 77.1%. This suggests that a vast majority of current locations growing avocado would be thermally suitable for having an understory coffee crop based on the metrics chosen here. While the validation effort was limited due to the lack of explicit geospatial data showing coffee growing locations in the state, our proxy validation using locations of avocados shows reasonable promise.

Modeled coffee suitability using climate projections for the 2021-2050 period and thermal management approaches shows a few changes relative to modern climate (Fig. 4). Warming results in avoidance of cold intolerance but increase in heat intolerance for locations along the fringes of where thermal suitability was marginal in modern climate. For example, there is reduced suitability for more interior coastal valleys as warming leads to more years where high temperatures extremes impacts crop viability. In coastal agricultural lands, however, warming reduces the occurrence of cold extremes and contributes to increased overall suitability. In addition, the overall warming eases overall energy constraints for near coastal agricultural lands in central California, which leads to a 50% statewide increase in lands thermally suitable for coffee.

Figure 5 provides a comparison of changes in thermally suitable cultivated lands for coffee (suitability $\geq 80\%$) under modern and future climates. We found a 50% increase in suitable agricultural lands statewide with future warming (236 km^2 to 355 km^2), due primarily to the increase in suitability in coastal agricultural zones from the greater San Francisco Bay Area southward to Santa Barbara County. In a few locations, such as those in warmer interior coastal valleys in San Diego County, areas suitable under modern climate become unsuitable due to heat extremes in a warmer climate (64.2 km^2 loss).

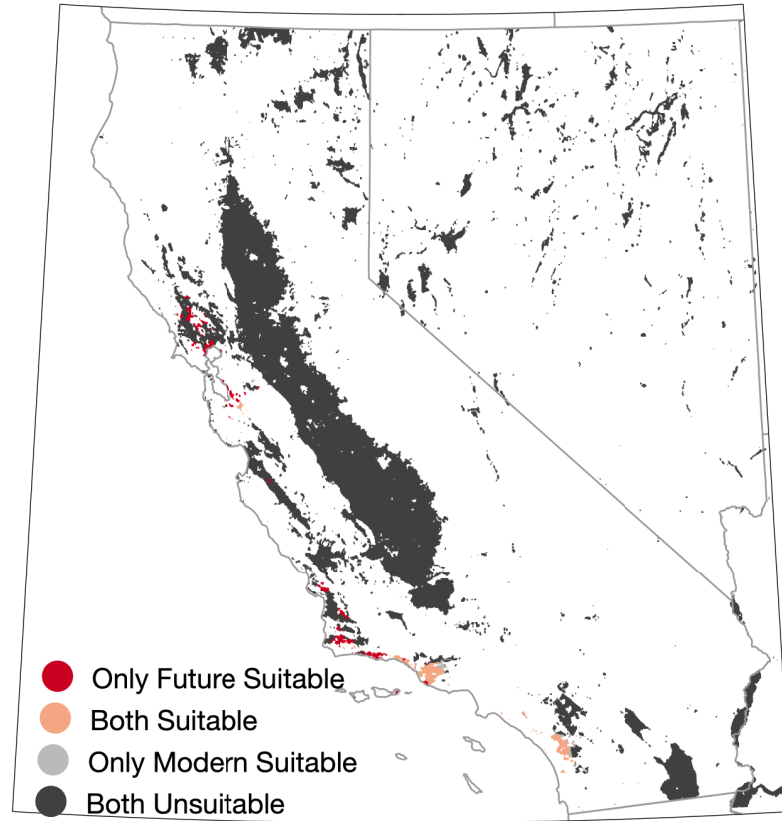


Figure 2.5: Changes in locations of thermally suitable climate (suitability $\geq 80\%$) for coffee under modern (1991-2020) and future (2021-2050) climates. Red indicates suitable climates only in future climate, light grey indicates suitable climates only in modern climate, peach indicates suitable climate for both modern and future climate, and dark grey indicates unsuitable climates for both periods. Non-cultivated lands are masked out in white.

2.5. Discussion

Our results show that modern climate of 1991-2020 is suitable for *C. arabica* cultivation for $\sim 236 \text{ km}^2$ of agricultural land in California. However, our quantified results suggest that such suitability is only feasible with thermal management strategies (e.g., crop shading agroforestry) that can buffer hot and cold extremes for a coffee understory crop. We identified geographic hotspots of thermal suitability for coffee within the belt between the Pacific Coast and coast ranges in central and southern California under modern climate, which corresponds with locations of sampled experimental coffee farms as well as the broader geography of avocado orchards in the state. We note that our

suitability estimates were performed using climate data at a ~4-km horizontal grid. As such, microclimates present in areas of complex topography (e.g., cold air drainages, ridge tops) may have different suitability than reported here when crop specific thresholds are crossed. Further, we did not assess soil suitability but do note that model results were constrained to existing agricultural lands indicating broad viability.

The modeling approach used here differs from the broader literature on coffee suitability, which typically uses species distribution modeling approaches based on climate summaries (Läderach *et al.*, 2017; Chemura *et al.*, 2021; Grüter *et al.*, 2022; Casilas, 2023). Species distribution modeling approaches often employ measures like mean annual temperature, average annual precipitation, and species presence data. However, given that coffee is predominantly grown today in the tropics and subtropics, the translation of such suitability assessments to new climate spaces including future climates and in mid-latitudes may be flawed (Fitzpatrick and Hargrove, 2009). Rather, the approach we take here uses biophysical thresholds from agronomic studies following work on other specialty crops that may be more translatable in space and time (Parker and Abatzoglou, 2017). We note that additional work should be done to assess whether the temperature thresholds for heat and cold intolerance as well as energy requirements for coffee cherry maturation taken from studies in the subtropics (Wintgens, 2004; Pezzopane *et al.*, 2008) hold for coffee growing in California.

One of our key findings is that coffee cultivation is very limited in the absence of management strategies to buffer heat and cold extremes. It is well known that mid-latitude climates have a much larger range of temperature variability than subtropical climates. Many management efforts are taken to protect cold and heat sensitive perennials (DaMatta and Ramalho, 2006) including overhead irrigation, air circulation, avoidance of planting in cold air drainages, plant acclimation, as well as canopy or shade tree implementation (DaMatta, 2004; Wintgens, 2004). The implementation of crops that co-exists with the physiological requirements of coffee, such as avocado, not only provide utility through thermal regulation of an understory crop but also provide a source of additional income for the farmer (Lin, 2007; Grüter *et al.*, 2022; Koutouleas *et al.*, 2022). Alternatively, integration of coffee plants with a mosaic of native vegetation may provide a working landscape with thermal protection for understory coffee plants while also providing ecosystem services (Viers *et al.*, 2013).

Numerous other considerations, external to the scope of this study, significantly constrain the viability of coffee cultivation. First, is that much of the suitable lands identified herein are in high-cost areas where agricultural land has been developed to suburban zones (Hart, 2001) and is home to some of the most expensive real estate in the United States. Cropland areas that are thermally suitable also have established high-value specialty crops (e.g., wine grapes, berries) and would require significant capital investment to incorporate coffee cultivation. Second is the cost consideration of coffee cultivation. Like other crops (e.g., olives, berries, grapes), high-quality coffee is handpicked to lessen damage and ensure fruit quality (Wintgens, 2004; Leroy *et al.*, 2006). Third, water scarcity is a growing concern in California given the overallocation

of surface and groundwater to agriculture and climate change (Grantham & Viers, 2014; Williams *et al.*, 2015). Lastly, we note that our near-term climate suitability is based on a very simple outlook of homogeneous warming by 1°C across the state during the next thirty years. However, uncertainty in regional climate predictions (Hawkins and Sutton, 2011) as well as potential changes in the moderating influence of maritime air and fog (Johnstone and Dawson, 2010) could be further considered.

Whether California becomes a new hotspot coffee growing region remains unknown. We estimate that over 230 km² of agricultural land is thermally suitable today with further increases across agricultural hubs in the Central Coast and Napa-Sonoma areas with continued warming. A small but distinct commercial specialty coffee market likely requires an expansion of farms currently found in the state. Hawaii and Puerto Rico have 28 km² and 19 km² of land harvesting coffee today, respectively (USDA, 2023a). The niche market for ultra-premium California grown coffee and potential ecotourism opportunities with coffee like that seen for wine and olive oil crops (Pulido-Fernández, Casado-Montilla and Carrillo-Hidalgo, 2019; Wolesi and Kumar, 2021) may encourage growth of the specialty crop in the state.

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CHAPTER 3. OLIVES AS A POTENTIAL WIN-WIN STRATEGY FOR SUSTAINABLE GROUNDWATER AND ECONOMIC FUTURES FOR CENTRAL VALLEY AGRICULTURE

3.1. Abstract

Agriculture in California's Central Valley produces diverse crops, mainly fruits, nuts, and vegetables, contributing over 80% of the agricultural value. However, perennial crops require annual irrigation, causing groundwater overdraft, especially in droughts. We explore olive cultivation as a promising agricultural commodity for a secure water and economic future. The entire Central Valley shows thermal suitability for olives and is expected to maintain this for at least the next three decades despite climate warming. Irrigation demand for olives is projected to rise by about 25 mm in the coming decades, a conservative estimate compared to other high-water-use perennials like almonds. The irrigation gap between olives and almonds grows during droughts, increasing water costs for almond production. Rising water prices due to the Sustainable Groundwater Management Act and climate change further widen the gap in water costs and profit margins, potentially encouraging olive cultivation. The demand for locally produced olive oil presents a significant opportunity to boost California's olive production, improving water security and promoting economic resilience among growers.

3.2. Introduction

California produces substantial quantities of high-value specialty crops, significantly contributing to both national and international food markets (CDFA, 2022). However, the elevated water demands and the inflexibility of certain crops in response to water shortages present challenges for farmers due to diminishing groundwater resources. Long-term groundwater overdraft in California's Central Valley has severely affected agriculture, rural communities, and ecosystems, particularly during the recent prolonged droughts intensified by climate change (Moyers et al., 2024). These stressors of drought and groundwater overdraft have prompted the implementation of the Sustainable Groundwater Management Act (SGMA), necessitating substantial modifications in water usage through agricultural land repurposing, conservation efforts, and modifications of cropping practices for groundwater-dependent lands.

To maintain agricultural production, broader planting of water-smart crops such as agave and grains such as amaranth and/or quinoa in the Central Valley should be considered necessary, and olives should be included. Olives present one such perennial crop with lower water requirements, drought hardiness to extreme deficit irrigation (Iniesta, Testi, Orgaz, & Lobos, 2009) and high economic value (Xinong, Sumner, & Matthews, 2014; Fine, 2023). Olives are grown across Mediterranean climates globally, with California's current production accounting for approximately 1.4% and 0.6% of global production of table and oil olives, respectively (Agricultural Marketing and Resource Center, 2024). Despite higher revenues from other crops, such as almonds, olive production in California has declined over the past four decades. Furthermore, California olive oil

production constitutes less than 2% of total U.S. consumption (Swearingen & Weber, 2024). The recent surge in consumer interest in olives, premium olive oil, and associated economic activities (including tourism, health, and sustainability) has revitalized attention on the California olive market (Hwang & Quadri-Felitti, 2021; Xinong et al., 2014; Sgroi et al., 2024; Elaydi & McLaughlin, 2012).

Transitioning to crops requiring less water yet providing profitability could alleviate immediate water restrictions during droughts and support long-term conservation efforts under SGMA. Crop selection should consider forward-looking climatic suitability, including thermal and watering requirements, while ensuring financial viability and adaptability to climate change. Given that almonds demand significantly more water and currently represent the largest share of cultivated land in California, there is potential utility in evaluating the potential of olives as a high-value, low-water-use alternative. This study investigates the climatic suitability of olives in California, utilizing climate data alongside thermal and phenological models, estimates their water needs under varying climate conditions, and conducts a simple cost-benefit analysis of water costs by substituting almonds with olives to evaluate economic and water trade-offs.

3.3. Methods

Geospatial data on olive cultivation in northern and central California were obtained from the 2021 US Department of Agriculture National Agriculture Statistics Service (USDA-NASS) Cropland Data Layer (CDL). We limited the suitability assessment to croplands with $\geq 1\%$ of annual and perennial crops during 2012-2021. Daily maximum and minimum temperatures and reference evapotranspiration (ET_o) from gridMET (Abatzoglou, 2013) for 1991-2020 assessed contemporary suitability. Given that gridMET slightly overestimates ET_o in heavily irrigated areas like California's Central Valley, a scalar correction of 0.85 was applied to daily ET_o (Schauer & Senay, 2019). Climate futures for the next three decades used output from 20 climate models in the Sixth Coupled Model Intercomparison Project. We superimposed multi-model changes in monthly temperature, precipitation, and ET_o between 2026-2055 and 1991-2020, calculated from climate model outputs to gridMET observations for comparison with current conditions (Abatzoglou et al., 2025).

We applied a semi-mechanistic thermal suitability modeling approach (e.g., Parker and Abatzoglou 2017), considering absolute temperature thresholds and heat and chill requirements for olives. Five specific requirements were examined: (i) cold hardiness, (ii) frost damage during flowering and fruit stages, (iii) chilling requirements, (iv) heat stress during flowering and fruiting, and (v) heat accumulation for maturation. These measures track thermal factors limiting productivity, from tree mortality (cold hardiness) to yield losses (frost damage, insufficient chill, unmet maturation requirements). Quantitative measures were taken from published literature based on field experiments, focusing on the Arbequina cultivar widely grown in California for olive oil (Table 1). For each growing year (Dec-Nov), we tabulated whether the five thermal growing requirements

were met. A year where all five met was considered potentially suitable for crop production. We quantify overall crop suitability as the percentage of years over the 30-year periods of analysis where all requirements were met.

Biophysical process	Threshold	Reference
Cold hardiness ¹	-12°C	Larcher, 1981
Chill requirement (CH)	7.2°C @200-300hr	Sibbett & Ferguson, 2005
Bloom (GDD)	540	Garrido, Fernández-González, Vázquez-Ruiz, & Rodríguez-Rajo, 2021
Frost ¹	-2°C	Sibbett & Ferguson, 2005
Heat during flowering ²	39°C	Lopez-Bernal, et al., 2018
Heat during fruiting ¹	48°C	Sibbett & Ferguson, 2005
Harvest (GDD)	2400	(Garrido, Fernández-González, Vázquez-Ruiz, & Rodríguez-Rajo, 2021

Table 3.1: Thermal thresholds in the olive suitability model include a base 7.2°C to calculate growing degree days (GDD). 1) A single day above this threshold is harmful. 2) Two consecutive days above this threshold during flowering are damaging.

Second, the demand for crop water was estimated utilizing established mid-season and end-season crop coefficients for olives. We specifically focus on crop coefficients for super-high-density planting of Arbequina, which is common in California. These crop coefficients are scaled by ETo to approximate crop water demand using phenological proxies for flowering and harvest to define the beginning and end of the mid-season, respectively. We presume the utilization of irrigation practices that ensure crops receive their complete water requirements. A water balance model was employed to estimate the unmet crop water demand, defined as the discrepancy between crop evapotranspiration and actual evapotranspiration (e.g., Abatzoglou et al., 2025).

Lastly, we conducted an analysis of water costs associated with olive production, juxtaposing these costs against almond output in a comparable region. This analysis considered three scenarios based on water costs from 2018 to 2023: (a) observed conditions, (b) projected water demands influenced by superposing the climate change signal for 2026 to 2055, and (c) changes in water demands attributable to the Sustainable Groundwater Management Act (SGMA) alongside the climate change perturbation. Rates are derived from the Porterville Irrigation District (Porterville Irrigation District, 2024). We applied the same methodological approach to almonds, utilizing the modeling of

Parker and Abatzoglou (2017) to estimate crop phenology, water demands, and irrigation needs.

Water costs per hectare is calculated by multiplying crop irrigation by the applicable water rate, presuming a 0.85 irrigation efficiency (Schauer & Senay, 2019) consistent with regional perennial cropping systems. This calculation does not account for additional expenses such as electricity, labor, or maintenance. The impact of SGMA on water prices remains uncertain; however, we assume a 60% escalation in future rates correlated with SGMA (Burlig, Preonas, & Woerman, 2024). We utilize three scenarios from 2018 to 2023: Present Conditions, Climate Change, and Climate Change with increased prices due to SGMA. Due to significant interannual hydroclimatic variability in the region, we compared drought years defined where water year types for the San Joaquin Valley were critically dry (2021 and 2022), and all other years as non-drought years, given the premise that water restrictions increase both irrigation requirements and water prices.

3.4. Results

3.4.1. Climate Suitability and Irrigation Requirements

From 1991 to 2020, most cultivated lands in the Central Valley exhibited thermal conditions conducive to olive production, with 85% categorized as having high suitability (≥ 9 out of 10 years satisfying thermal prerequisites). Areas of low suitability comprised maritime locations in central California, constrained by an inadequate accumulation of growing degree days essential for fruit maturation and insufficient chill hours. Heat stress during the flowering period presented a minor concern in the San Joaquin Valley. The average suitability calculated over croplands with at least 1% of land with olives as of 2021 was 95%.

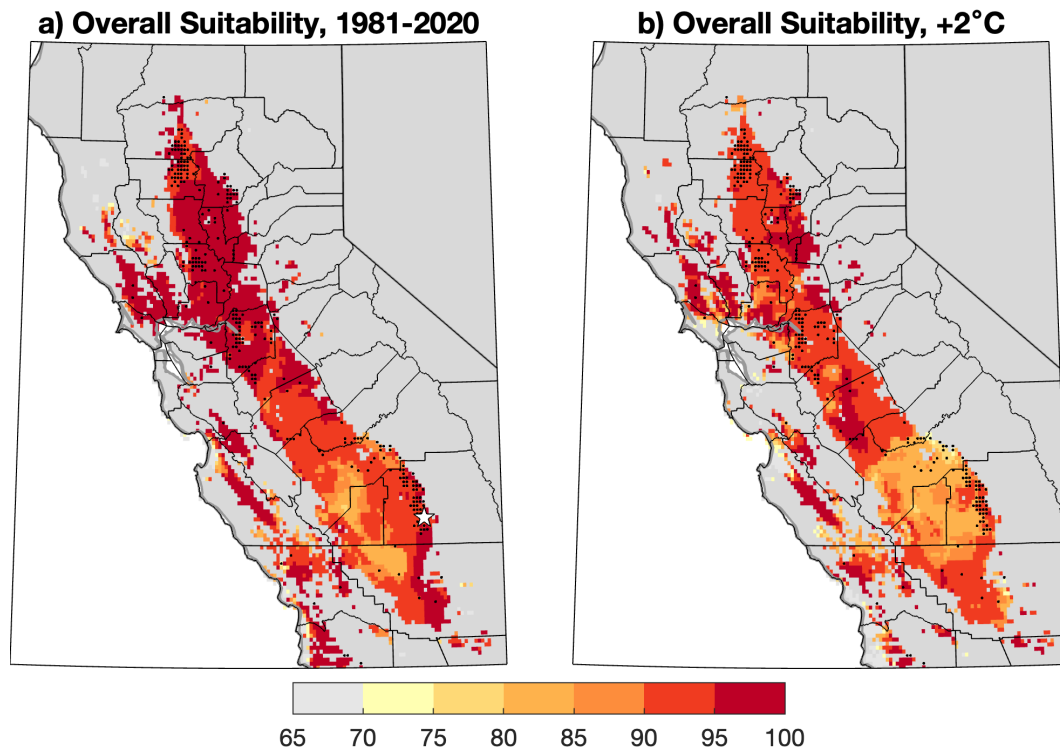


Figure 3.1: The thermal climate suitability for olive cultivation, considering (a) historical climate data from 1991 to 2020, and (b) projections from 2026 to 2055, showing the percentage of years that satisfied all thermal requirements for successful cultivation. Areas designated with less than 1% agricultural land as of 2021 are indicated in dark grey. Black dots represent locations with at least 1% of olive production during the growing season of 2021. In panel (a), the white star symbolizes the representative farm near Porterville, used in economic analysis.

Climate projections for the period 2026 to 2055 indicate a high suitability for olive cultivation across a substantial majority (67%) of cultivated lands (Fig. 1b). Nevertheless, a decline in suitability is projected in the south-central region of the San Joaquin Valley, alongside a slight decrease in the southern Sacramento Valley, attributed to an increased vulnerability to heat stress during the flowering period (Fig. 2g). Implementing management techniques such as dusting with Kaolin clay powder or utilizing modified irrigation methods may assist in alleviating these adverse effects (Fraga, Moriondo, Leolini, & Santos, 2021). For comparison, we find the average thermal suitability of lands currently planted in olives of 90% – only a minor reduction compared with contemporary climate.

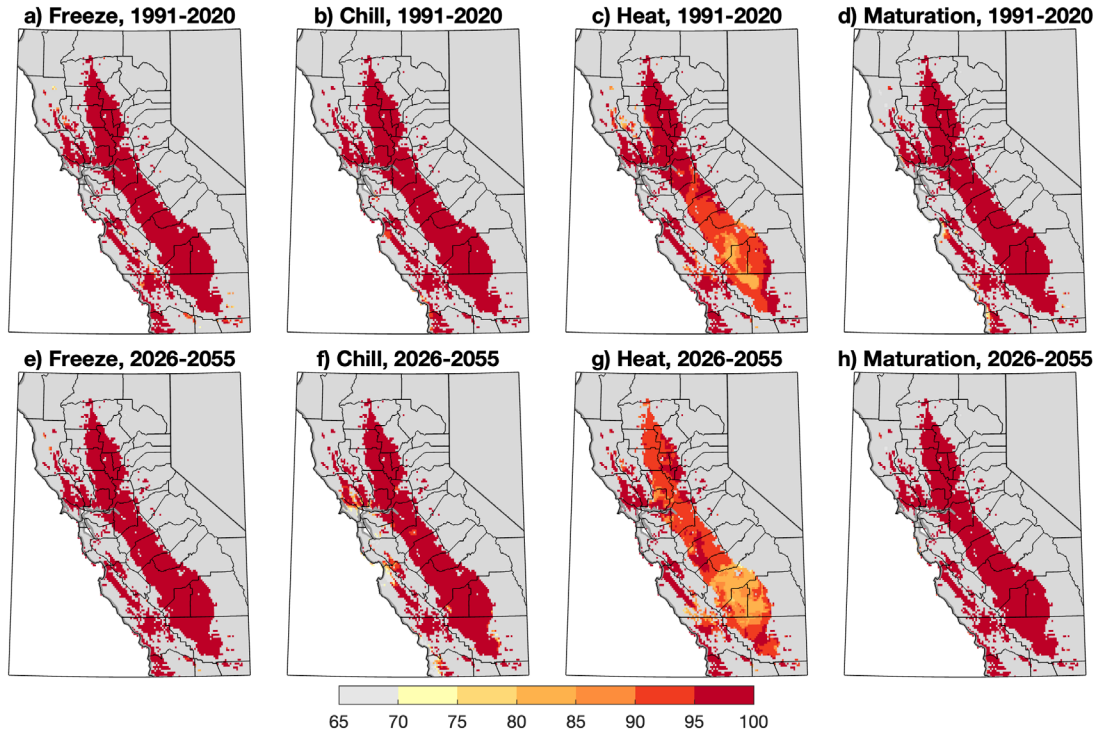


Figure 3.2: Percent of years suitable for olives under observed (1991-2020) and future climate (2026-2055) for (a, e) avoiding freeze or frost damage, (b, f) having sufficient winter chill, (c,g) avoiding heat stress during flowering and fruiting, and (d,h) having sufficient heat for maturation.

Annual irrigation requirements for olive cultivation in central California range from 250 to 700 millimeters, with a higher amount in the southern San Joaquin Valley (Fig. 3a). Certain water requirements are satisfied through precipitation and soil moisture retention. Between 2026 and 2055, the crop water demand for olives will increase by about 15 to 30 millimeters per year across much of the Central Valley (Fig. 3b).

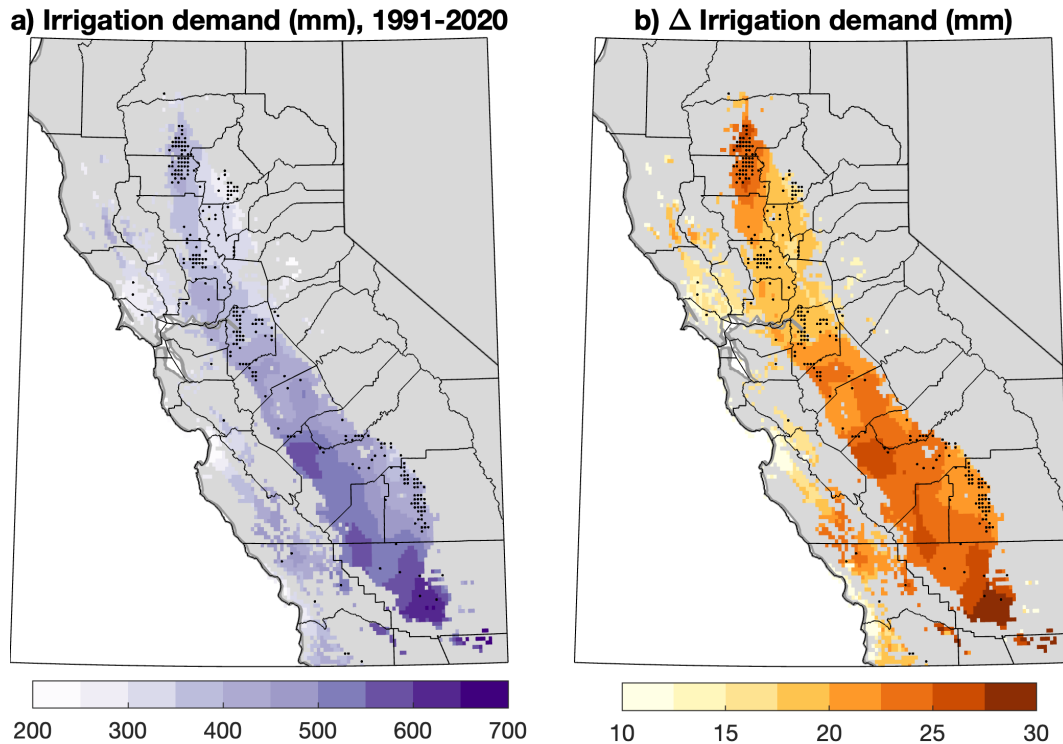


Figure 3.3: Average annual irrigation demand for high-density Arbequina olive for (a) historical 1991-2020, and (b) the additional irrigation demand during 2026-2055. Black dots denote locations that had $\geq 1\%$ of olive during the 2021 growing season.

3.4.2. Water Costs

The analysis of water costs reveals much higher irrigation needs for almonds than olives. In non-drought conditions, the almond crop located near Porterville requires an annual average of 1139 mm of water, whereas the olive crop requires 609 mm. During periods of drought, this demand escalates to 1302 mm for almonds and 767 mm for olives. Due to the next 30 years of climate change, irrigation requirements increase by about 50 mm for almonds and 25 mm for olives, augmenting overall water needs.

Translating this information into water costs associated with irrigation, while factoring in the prevailing irrigation efficiency, indicates that under non-drought conditions, water costs amount to \$666/ha for almonds and \$357/ha for olives (Fig. 4). In years characterized by drought with elevated irrigation needs, these costs escalate to \$3634/ha for almonds and \$2115/ha for olives. The ramifications of climate change on irrigation demands result in an increase of \$19.77-\$29.65 per hectare in water costs during non-drought years and an increase of \$71.66-\$155.68 per hectare during drought years, with more pronounced escalations for almonds. Given the higher water prices associated with the Sustainable Groundwater Management Act (SGMA), coupled with climate change, even more substantial increases in water costs are anticipated. It is estimated that irrigation expenses for almonds will reach \$1114/ha and \$6066/ha in non-drought and drought years, respectively, compared to olives, whose costs are projected to rise to \$602

/ha and \$3501 /ha under the same conditions. Therefore, under prospective climate conditions and SGMA regulations, both crops encounter rising water costs; however, the heightened water requirements of almonds may disproportionately affect profitability compared to olives.

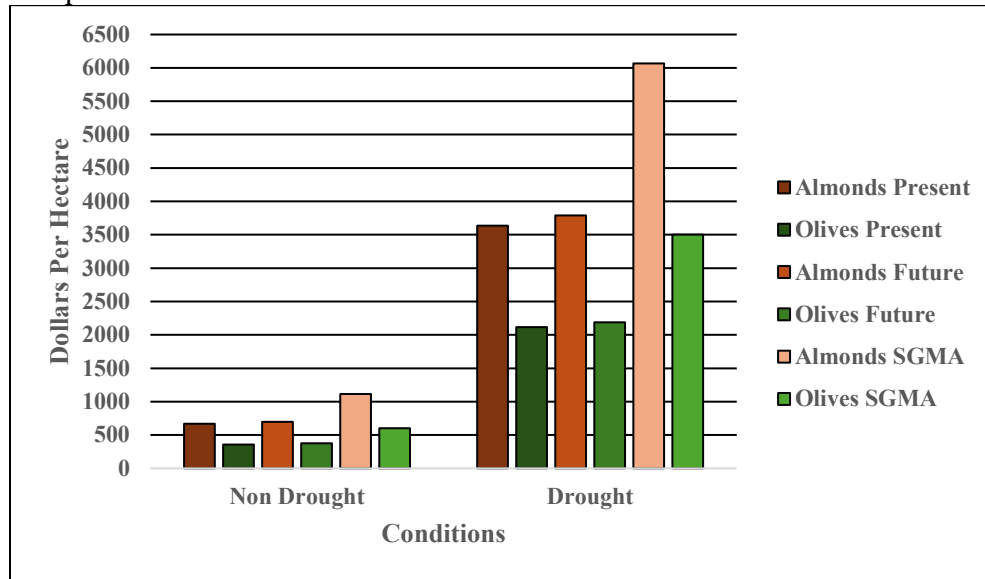


Figure 3.4: Compiled from Parker and Abatzoglou 2017; Schauer & Senay, 2019; Burlig, Preonas, & Woerman, 2024; Porterville Irrigation District, 2024. The average irrigation costs for non-drought and drought years associated with representative hectares of almond and olive cultivation in Tulare County are presented herein. The results encompass current conditions spanning from 2018 to 2023, projected future climate scenarios for the ensuing thirty years, and future climate scenarios augmented by the effects of the Sustainable Groundwater Management Act (SGMA).

3.5. Discussion

Our research shows most agricultural land in the Central Valley is suitable for olive cultivation and will remain climatically suitable with a warming climate. Compared to other high-value perennials such as almonds, olives have much lower irrigation requirements, thus providing a groundwork vehicle to comply with for SGMA and be economically viable. Although not discussed in this paper it is theorized that this may further supported by management techniques such as implementation of low or medium density orchard planting schemes (7 to 9 m apart) that can be either mechanical with light equipment and or hand harvested yet most critical to the scope this paper, can also be dry farmed. (Vosen, 2010; UNAR, 2024; Santa Cruz Olive Tree Nursery, 2025). However, we show that additional warming may result in some heat affecting olives during key phenological periods such as flowering and fruiting, particularly in the southern San Joaquin Valley (Benlloch-Gonzalez, Sanchez-Lucas, Benlloch, & Fernandez-Escobar, 2018) (Wortmann, Biton, Zemach, Many, & Ben-Ari, 2024). These impacts may be

mitigated through management efforts and adaptation strategies, such as a general strategy of crop irrigation techniques and other heat preventative methodologies, in addition to cultivar selection (Wortmann, Biton, Zemach, Many, & Ben-Ari, 2024; Fraga, Moriondo, Leolini, & Santos, 2021).

At present, almonds are associated with a higher market value than olives; however, it is important to note that we do not consider the variability in crop prices, which remain uncertain. Focusing exclusively on water costs for irrigation utilizing present cost data, we find that while the direct effect of climate change leads to higher water costs through increased irrigation demand, the influence of SGMA vastly supersedes and compounds the direct climate influence on water prices. This model does not consider present market conditions. The escalating water costs for almonds relative to olives under climate change and SGMA come from the higher water demands of almonds. While present day market prices may allow almonds to be more profitable than olives under climate change and SGMA scenarios, the differences in net profit between the two significantly narrow due to higher water costs, particularly during drought years that may become more frequent (McEvoy, Pierce, Kalansky, Cayan, & Abatzoglou, 2020). This finding implies that diversifying into crops with lower water utilization, such as olives, could bolster both water and economic security under the SGMA framework.

The popularity of olive oil in the United States has significantly increased, with domestic production currently fulfilling only approximately 2% of the olive oil market (International Olive Council, 2024). However, reliance on imports introduces various risks. Climatic changes in Mediterranean regions may result in reduced yields and quality, thereby elevating olive import prices, while potential tariffs could incentivize domestic production. Consequently, the expansion of olive cultivation in California could yield advantages such as water conservation and economic diversification. However, this growth is hindered by inadequate post-farm infrastructure and market-related factors. Nevertheless, favorable climatic conditions may facilitate an increase in the supply of California-produced olive products, contribute to the sustainability of groundwater resources, and provide growers with a lower-risk, high-value crop opportunity in the future.

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CHAPTER 4: SAFFRON AS A HIGH-VALUE LOW-WATER CLIMATE SMART SPECIALTY CROP IN THE SAN JOAQUIN VALLEY

4.1. Abstract

California's San Joaquin Valley (SJV) faces intensifying water scarcity under the Sustainable Groundwater Management Act (SGMA). This study evaluates saffron (*Crocus sativus* L.) as a climate-smart, high-value crop for low-water agricultural systems through assessment of climate suitability, flood risk, and intercropping potential. Nearly all agricultural lands in the SJV are thermally suitable, and over 4 million acres meet both hydrological and flood-tolerance thresholds. Saffron's low water requirement (~260 mm yr⁻¹) and dormancy during peak irrigation months make it compatible with water-limited conditions. Grapes and olives emerge as optimal intercrops given their efficient drip-irrigation systems and offset harvest periods. While labor intensity remains a constraint, advances in mechanization are expected to improve feasibility. By aligning minimal irrigation demand, saffron provides an economically resilient diversification option for Central Valley farmers adapting to reduced groundwater allocations.

4.2. Introduction

California's agriculture sector is vulnerable to water scarcity stressors – particularly in groundwater dependent lands in the San Joaquin Valley (Hanak, et al., 2023; Peterson, Pittelkow, Lundy, & Collins, 2022; Grantham & Viers, 2014). These existent challenges are now compounded by ongoing climate change impacts and the Sustainable Groundwater management Act (SGMA) prompting economic concerns about the future of agriculture in impacted parts of the state. While numerous land repurposing strategies taking land out of agricultural production are on the table, shifts in crop management and crop substitution towards increased water-utility may be an economically and environmentally viable solution.

Here, I highlight the opportunities for Saffron (*Crocus sativus* L.) as a specialty crop that fits these criteria yet has thus far been sparingly grown in California. Saffron is endemic to arid to semi-arid climates including being grown in several Mediterranean climates, and hence likely well suited to much of the Central Valley. Furthermore, it has a unique physiology allowing for minimal water requirements as it is dormant in the summer – requiring water primarily in the fall and spring which can allow for it to grown as a dryland crop in some areas.

Saffron is the most expensive spice in the world fetching in the United States \$25-100/g as of 2018. However, several factors limit the uptake of saffron cultivation. First, the high costs are due to the intense labor requirement for harvesting. The labor costs are often cited as a deterrent to wider scale production by small farms founded on the large amounts needed for economic viability and that the flowers and other profitable segments must be picked and separated by hand to mitigate damage and ensure quality. No mechanized harvest application is presently known for commercial use; however,

attempts are being made to automate key nodes (harvesting) within the saffron cultivation process (Saeidirad, 2020) suggestive that advances in autonomous harvest technologies may overcome these challenges. Second, the lack of familiarity with saffron cultivations and markets has also hindered incorporating the crop in the US. However, the potential economic benefits of saffron cultivation may help alleviate effects associated with water scarcity and climate change while promoting agricultural diversity and additional economic benefits, particularly to small farmers.

a. Why Saffron?

Crop choices often involve efforts to optimize profit based on the collection of costs to product and market value of the product. In addition to saffron's high market prices, prices in traditional producing regions have risen steadily since 2010 (Skinner et al., 2021a). With ongoing conflict and impacts of climate change upon traditional saffron growing regions combined with global tariffs, saffron prices are expected to further escalate in countries like the US. Yet, saffron currently is costly to cultivate due to its intensive labor requirements thus stifling adoption in the United States.

Saffron's versatility across culinary, medicinal, cosmetic, and textile industries underpins its strong market potential (Kumar et al., 2008; Koochehi & Khajeh-Hosseini, 2020, Singletary 2020). Its active compounds crocin, picrocrocin, and safranal, are responsible for its color, aroma, and flavor, and serve as quality indicators (Skinner et al., 2017; Kumar et al., 2008). Culinary applications are particularly strong in Middle Eastern, Mediterranean, and Indian cuisines, with saffron also widely used as a natural food coloring (Khorasanchi et al., 2018).

Medicinal research indicates potential benefits in managing depression, epilepsy, Alzheimer's disease, mild cognitive impairment, type 2 diabetes, metabolic syndrome, cardiovascular disease, inflammation, anxiety, and respiratory conditions (Denys, C.J. 2013; Koochehi & Khajeh-Hosseini, 2020; Lu et al., 2021). Certain studies indicate possible anti-carcinogenic effects (Khorasanchi et al., 2018; Varghese et al 2025), though no conclusive human clinical trials exist. Saffron is also used in textile dyes and perfumes (Dai, Nik, & Hong-Xi, 2021).

1. This multidimensional demand contributed in a global value for saffron of approximately 266 million dollars in 2023 with the three top producing countries of Iran, Spain, and Afghanistan responsible for exporting 43.4%, 23.3%, and 21.4% of the world export market for saffron (collectively 90% of global export market), respectively (Fig. 1; (Observatory of Economic Complexity (OEC), n.d.) (Mirza & Kulcsar, About Saffron, 2025). Small-scale commercial production has emerged in cooler climates such as Vermont with commercial operations primarily in backyard and hobby farms (Ayari et al., 2022; Skinner et al., 2021b; Gresta, et al. 2007)

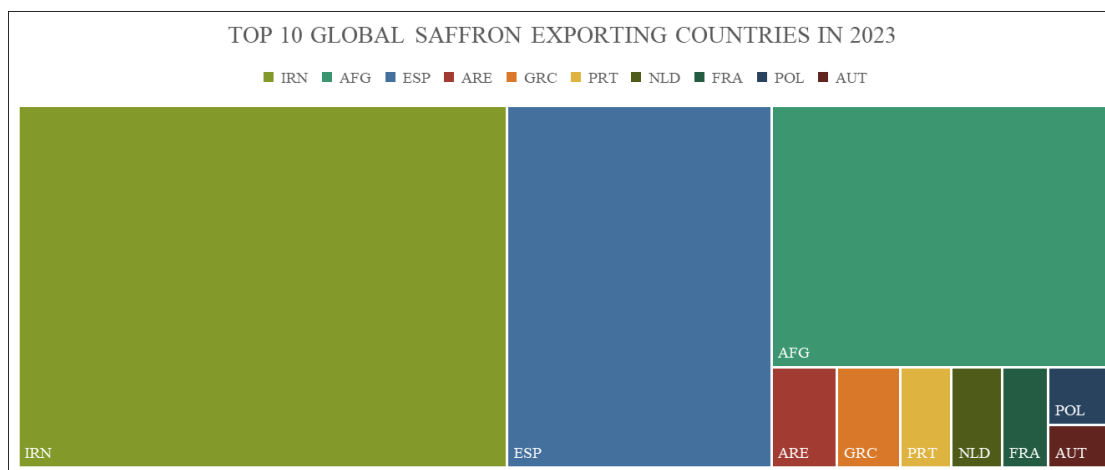


Figure 4.1: Global export market for Saffron as of 2023 derived from Data provided by (Observatory of Economic Complexity (OEC), n.d.). The leading exporters are Iran (IRN), Spain (ESP), Afghanistan (AFG), United Arab Emirates (UAE), Greece (GRC), Portugal (PRT), Netherland (NLD), France (FRA) Poland (POL) and Austria (AUT).

b. Cultivating saffron

Saffron (*Crocus sativus L.*) is a perennial plant endemic to Mediterranean climates, with a history of cultivation spanning approximately 3,500 years. Saffron can grow across diverse arid and semi-arid environments, attributable to its distinct adaptive features; specifically narrow-rigid leaves that limit transpiration as well as limited nutrients and soil requirements (Koocheki, Moghaddam, & Seyyedi, Saffron-pumpkin/watermelon: A clean and sustainable strategy for increasing economic land equivalent ratio under limited irrigation, 2019; Mirza & Kulcsar, About Saffron, 2025). As a result, saffron requires significantly less water than numerous agricultural crops, making it an attractive specialty crop in areas with limited water resources. Unlike many crops whose water demands peak during the warm growing season, the primary water needs for saffron are between October and mid-May and are often satisfied by seasonal precipitation in some regions as a dryland crop or with limited irrigation needs (Koocheki, Fallahi, & Jami Al-Ahmadi, 2020), with the plant being dormant during the core summer months (Skinner, Parker, & Ghalehbolabbahani, 2017; Koocheki et al., 2020).

Harvesting is the most financially costly stage of saffron cultivation, thus hindering large scale adoption of this crop. Harvesting was identified as the most labor- and time-intensive stage of saffron production. The procedure involving harvesting is conducted in three sequential steps, following international quality benchmarks.

1. Flower Collection. Blossoms are removed from the stem during early morning hours (typically between early morning, or late afternoon in non-arid regions) to

maintain freshness and preserve volatile compounds essential to saffron quality (Skinner, Parker, & GhalehgoLabbehbahani 2021c). Flowers are collected manually into shallow baskets to prevent compression damage.

2. **Separation.** Immediately after harvest, individual flowers are dissected to isolate their three floral components: red stigmas, yellow stamens, and purple petals. Stigmas are carefully detached at their base to avoid fragmentation, since intact filaments are required for premium grading.
3. **Drying and Packaging.** Fresh stigmas are dried under controlled conditions at 50–80 °C for 30–60 minutes, using either forced-air ovens or desiccation chambers, until a target moisture content of 8–12% was achieved (Koocheki A., 2020b; ISO 2019). However it is noted that other methods exist regarding this process (Koocheki A. , 2020; Skinner, Parker, & GhalehgoLabbehbahani, 2021b; Mirza & Kulcsar, About Saffron, 2025). Following drying, stigmas were immediately sealed in airtight, light-resistant containers to prevent oxidation and loss of volatile compounds (Koocheki A. , 2020; Mirza & Kulcsar, About Saffron, 2025).



Figure 4.2: Saffron Flower (Photo K. Prewitt)

Harvest of saffron currently, is entirely manual (Saeidirad, 2020), taking about 13 minutes to harvest one hundred flowers and 23 minutes for separation. With 167 flowers needed for just one gram of saffron (Skinner et al., 2020), mechanization is necessary. Machine development faces obstacles due to established cultivation practices and the genetic uniformity of saffron, which complicate automation. Such factors make saffron economically unviable for most farmers in the United States. Nevertheless, technological innovation holds the potential to reduce labor costs, improve efficiency, and enhance product quality by minimizing contamination (Saeidirad, 2020).

However, for small, diversified farms, integrating saffron into a portfolio strategy alongside lower-cost crops may offset risk and enhance overall profitability (Skinner, Parker, & Ghalehgholabbehbahani, 2021a). Mechanization therefore emerges as both an economic necessity and a quality assurance strategy, reducing labor inputs, lowering costs, and minimizing contamination risks while preserving ISO-compliant (ISO, 2019) quality standards. These innovations could strengthen California saffron's competitiveness in global markets and improve farm-level sustainability.

c. Part of a solution for pressing water issues in the San Joaquin Valley?

California's San Joaquin Valley (SJV) faces increasingly severe droughts, rising temperatures, and declining groundwater reserves (Peterson et al., 2022; Hanak et al., 2023). California's specialty crops are economically valuable but often water-intensive, with many unable to adapt quickly to changing water availability (CDFA, 2023;). Chronic groundwater overdraft has damaged agriculture, rural communities, and ecosystems, particularly during recent multi-year droughts exacerbated by climate change (Moyers et al., 2024).

Within this context, SGMA provides a framework for balancing water use over time by encouraging a combination of land repurposing, conservation, and crop diversification (Hanak et al., 2023; Peterson et al., 2022; Medellín-Azuara et al., 2024). Transitions away from portions of irrigated acreage are likely to be challenging for producers and communities but also create space to consider alternative or novel agricultural systems that use less water while maintaining economic activity. Saffron's agronomic characteristics and market value position it as one potential option concerning issues of water utility such as groundwater overdraft and other hydrologic concerns in climate change adaptation and mitigation,

Low-water-use crops can provide environmental and economic benefits for some agricultural producers (Hanak et al., 2023; Koocheki et al., 2019; Peterson et al., 2022). With low water requirements and broad market demand (Mirza & Kulcsar, 2025), saffron represents an option for introduction into the region as part of efficient and diversified farming systems. In addition, its autumn flowering allows intercropping with existing cropping systems. Intercropping may be a viable option for small farmers to incorporate saffron cultivation in existing crop systems rather than having separate land devoted to saffron cultivation. This can reduce land-use conflict and increase overall farm productivity and diversity, including resilience to variability in water resources.

In this chapter I explore three questions related to the viability of saffron cultivation in California. First, I map out the climatic suitability of saffron across the region based on existing literature. Second, as flooding harms saffron and companion crops, I overlay 100-year flood zone maps to identify croplands that may be subject to low-probability high-impact flooding. These two questions in tandem can help pinpoint potential cultivation areas in the state. Finally, I conduct a survey of intercropping potential for

saffron with existing crops grown in the San Joaquin Valley to highlight potential opportunities for growers to complement their current crop portfolios.

4.3. Methods

This study applies a three-stage framework to assess the viability of saffron cultivation in California. First, climatic suitability was evaluated by mapping saffron's water requirements and thermal tolerance across the state to identify zones suitable for cultivation. Second, flooding risk was incorporated, given saffron's sensitivity to excess soil moisture and corm rot (Rezvani, Sorooshzadeh, & Farhadi, 2012). Suitability zones are defined by overlaying the 100-year floodplain boundaries to assess hydrological risk. Third, intercropping potential was assessed by surveying existing San Joaquin Valley crops based on a literature review of crop water, soil, and harvest requirements. Together, these three factors climatic suitability, hydrological exposure, and cropping-system integration form an initial basis for identifying opportunities and constraints in the introduction of saffron as a climate-resilient, high-value crop in California.

a. Climate: Temperature and Water Requirements

Saffron's phenological characteristics make it well-suited to many regions of the San Joaquin Valley, particularly those most affected by drought and heat stress. However, as with any organism, saffron is subject to environmental thresholds that may adversely affect or limit its development. Extended periods of temperatures above 40 °C significantly elevate evapotranspiration and reduce soil moisture, necessitating supplemental irrigation to sustain corm viability and development during saffron's dormancy phase (Rezvani-Moghaddam, 2020). Exposure to temperatures exceeding 45 °C is particularly damaging prolonged thermal stress can impair flower initiation, disrupt physiological processes, and cause corm desiccation or mortality, ultimately reducing flowering and yield (Molina et al., 2004). Conversely, exposure to temperatures below -22 °C during the winter growing season may suppress flowering and inhibit shoot emergence((Kumar, et al., 2009; Rezvani-Moghaddam, 2020; Gheshm & Brown, 2021)Given that flowering represents the sole stage in which economically valuable floral components (stigmas, stamens, and petals) are produced, temperature exerts a decisive influence on the overall productivity of saffron.

Heat hardiness	45°C	(Rezvani-Moghaddam, 2020)
Cold hardiness	-22°C	(Gheshm & Brown, 2021).

Water requirements	260 mm	(Koocheki et al., 2020; Mirza & Kulcsar, 2025).
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Table 4.1: Climate suitability requirements for saffron.

Annual evapotranspiration (ET_c) or water use for saffron is about 260mm, primarily from October to April (Koocheki, 2020a; Mirza & Kulcsar 2025). As saffron is dormant during the summer months, crop water demand is not required during these months, supporting water conservation goals (Hanak, et al., 2023; Cole, et al., 2024). However, irrigation may be unnecessary or limited to supplemental applications during extreme heat events (>40°C) as a mitigation effort, particularly outside of the dormancy period.

Rather than use retrospective climate data to assess future climate suitability, I used statistically downscaled climate projections from 20 climate models (GCM) participating in the Coupled Model Inter-comparison Project 5 (CMIP5) centered on present day conditions (2010-2039) for a moderate emission scenario (RCP4.5). Climate data was downscaled with the Multivariate Adaptive Constructed Analogs (MACA) downscaling approach (Abatzoglou 2013) using gridMET, a ~4-km horizontal resolution daily observational data for training.

I used 30-year climate summaries (2010–2039) of the average lowest minimum daily temperature per year, average highest maximum daily temperature per year, and annual total precipitation to approximate cold hardiness, heat hardiness, and water requirements for saffron. A region is considered thermally suitable when both temperature requirements are met (i.e., the average coldest night per year is warmer than -22 °C and the hottest day per year remains below 45 °C). I furthermore consider a region to be potentially suitable for on-farm precipitation when local annual precipitation exceeds saffron’s water requirement (~260 mm yr⁻¹).

However, the latter classification does not imply that saffron is inherently suited to dryland farming. Although the crop exhibits strong drought tolerance due to its summer dormancy, successful production depends on the timing of moisture relative to phenological stages particularly during autumn flowering and spring vegetative growth. Therefore, the “on-farm precipitation” category should be interpreted as indicating zones where only nominal supplemental irrigation would be needed, rather than areas capable of sustaining purely rainfed production. This approach follows FAO (2020) and UC ANR (2020) guidance emphasizing the importance of aligning seasonal precipitation patterns with crop water demand for limited-irrigation production systems.

b. Flood Hazard

Although saffron can be cultivated on a wide range of well drained soils (Shahandeh, 2020), it is highly intolerant of flooding. Excess soil moisture can rapidly lead to corm rot and crop failure (Masudi et al., 2025; Rezvani et al., 2012). Flooding impacts are compounded in alluvial landscapes where deposition of fine silt layers following inundation can reduce soil fertility and alter physical properties important for saffron development (Shahandeh, 2020; De Feudis et al., 2025). California provides a relevant example: the state has a long history of severe flooding, ranging from the Great Flood of 1861–62 to the destructive events of 1950 and 1969, and most recently the widespread inundations of 2023. For a crop such as saffron, the prospect of flood events poses a significant agronomic and economic challenge to its successful integration into California’s agricultural landscape if cultivated in elevated at risk regions such as flood-prone or low-lying regions (Bark, R.H. 2021)

I use the 100-year flood risk data from FEMA to approximate areas that currently have a 1% risk of inundation annually. While climate change and subsidence have and will continue to alter the risk zones, the current 100-year flood risk map provides a starting basis for excluding cropland subject to inundation.

I quantified the extent of suitable agricultural lands meeting thermal, thermal and water, and outside of the 100-year flood risk zones across the San Joaquin Valley. To accomplish this, I used the 2024 Cropland Data Layer (CDL) data from the United States Department of Agriculture to identify all agricultural lands within the San Joaquin Valley, masking out non-agricultural land covers (e.g., urban). These CDL polygons were then overlaid with the thermal suitability, precipitation, and flood-risk layers described using ArcGIS Pro. Resulting acreage totals were aggregated by county, to quantify the extent of agricultural land suitable for saffron cultivation.

c. Partner Crop and Site Selection

The primary objective of water management in saffron cultivation is to minimize water use while maximizing profitability (Bryant et al., 2020) While saffron may be cultivated in individual plots, it also has strong potential to be introduced through intercropping systems. Pairing saffron with other high-value, low-water-use crops allows irrigation and management strategies to be designed around the most water-demanding species in the system, thereby reducing crop injury and maximizing resource efficiency. Intercropping can also promote positive symbiotic relationships that enhance overall crop development, yield stability, and soil quality (Qiu et al., 2025).

Based on their economic payoff, relative water requirements, and overall value, potential companion crops for saffron include grapes (Tao et al., 2024), olives (González-Rosado, Parras-Alcántara, Aguilera-Huertas, & Lozano-García, 2022), almonds (Kumar et al., 2008), chickpeas (Mohammadkhani, Pouryousef, & Yousefi, 2023), pumpkins, and watermelons (Koocheki, Moghaddam, & Seyyedi 2019) California is a national leader in the production of all these crops and holds important positions at the global level. For grapes, California dominates U.S. production, while Italy, France, Spain, and the United

States rank among the world’s largest producers (Food and Agriculture Organization [FAO], 2023; U.S. Department of Agriculture [USDA], 2024). By contrast, U.S. olive production is limited, with global leadership concentrated in Spain, Greece, and Turkey; nevertheless, California accounts for 95% of domestic output (International Olive Council [IOC], 2023). For watermelons and pumpkins, California contributes significantly at the national level but is not a global leader (FAO, 2023). Chickpea production in California remains modest, with India and Australia serving as the principal global producers (FAO, 2023; USDA National Agricultural Statistics Service [NASS], 2024).

Intercropping suitability was evaluated using a decision matrix structured around three factors: water requirements, harvest and mechanization compatibility, and economic value. These were selected based on prior saffron feasibility assessments (Husaini, 2014; Koocheki, 2020; Kumar et al., 2008). To maintain replicability and avoid overfitting the analysis, each factor was scored using a binary approach, rather than a continuous scale, thereby highlighting clear thresholds of suitability relevant to farm-level decision making using the following criteria:

1. Water requirements: if the combined crop evapotranspiration (ET_c) of partner crop did not exceed 1,000 mm annually (Husaini, 2014; Koocheki et al., 2020a Allen et al. 1998). Prior studies have shown that saffron performs poorly in areas receiving more than 1,000 mm of annual precipitation because prolonged soil saturation promotes corm rot, fungal disease, and reduced flowering. At these moisture levels, saffron loses its typical dry-season dormancy response and experiences physiological stress.
2. Harvest compatibility: if mechanized harvests did not overlap with saffron’s hand-harvest season and did not disrupt saffron during their dormant stage (University of California, Davis, 2018, 2024).
3. Economic value: was defined as the ten-year average gross cash receipts per acre for each target crop, calculated by dividing the total statewide crop value (cash receipts) by the corresponding harvested or bearing acreage as reported by the California Department of Food and Agriculture (CDFA).

Crop	Ten-Year Average Value (\$ 1,000)	Average Harvested/Bearing Acres	Economic Value (\$ per acre)	Notes
Almonds	5,775,000	1,120,000	5,160	High-value perennial; alternate bearing smoothed.

Grapes (all)	5,550,000	850,000	6,530	Stable export-driven perennial.
Olives	111,000	40,000	2,780	Pronounced alternate-bearing cycle; 10-year mean used.
Watermelons	121,000	12,000	10,080	Short-season annual; high market return, small acreage.
Pumpkins	26,300	5,000	5,260	Short-season specialty crop.
Chickpeas (Garbanzo)	215 (2021–2023 mean)	3,000	1,290	Low-value rotational legume.

Table 4.2. Ten-Year Average Economic Value per Acre for Selected California Crops (2014–2023) compiled from the CDFA California Agricultural Statistics Review 2022–2023 and 2023–2024 Values were compiled from the CDFA California Agricultural Statistics Review 2022–2023 and 2023–2024 and represent gross receipts per acre rather than net profit. Accordingly, these data serve as a comparative metric of statewide market value and resource efficiency rather than an estimate of farm-level profitability.

The binary framework functioned as a conceptual filter rather than a statistical model, indicating whether a crop met or failed to meet saffron’s agronomic thresholds. The full quantitative analysis, presented in the Results section, then integrates these suitability factors with county-level acreage data derived from GIS overlays of thermal, precipitation, and flood-risk layers.

4.5. Results

4.5.1. Climatic Suitability of Saffron

Nearly all of the San Joaquin Valley (SJV) demonstrates high climatic suitability for saffron (*Crocus sativus* L.) cultivation. Cold hardiness is not constraint for saffron production across the region, and very limited geographic areas mainly those without current agricultural production are projected to have summer heat extremes exceeding saffron’s upper heat tolerance threshold of 45°C during 2010-2039 (Figure 3). Limited pockets of reduced suitability appear near Fresno and Tulare, likely reflecting localized

heat-stress extremes that exceed the upper phenological limits for saffron flowering and dormancy (Husaini , 2014). Moreover, for occasional temperatures exceeding such thresholds, current management practices such as optimized irrigation scheduling can mitigate heat stress impacts on saffron (Husaini, 2014; Koocheki, 2020).

Much of the valley floor in the SJV receives insufficient annual precipitation to directly meet modest saffron water needs. However, the eastern stretch of the valley, particularly north of Merced and the adjacent Sierra Nevada foothills and coastal ranges receive enough annual precipitation to satisfy saffron water demands noting the mismatch in timing mentioned earlier. Most of the SJV and adjacent regions would need nominal irrigation during the fall and spring to supplement winter precipitation to satisfy water demands of saffron.

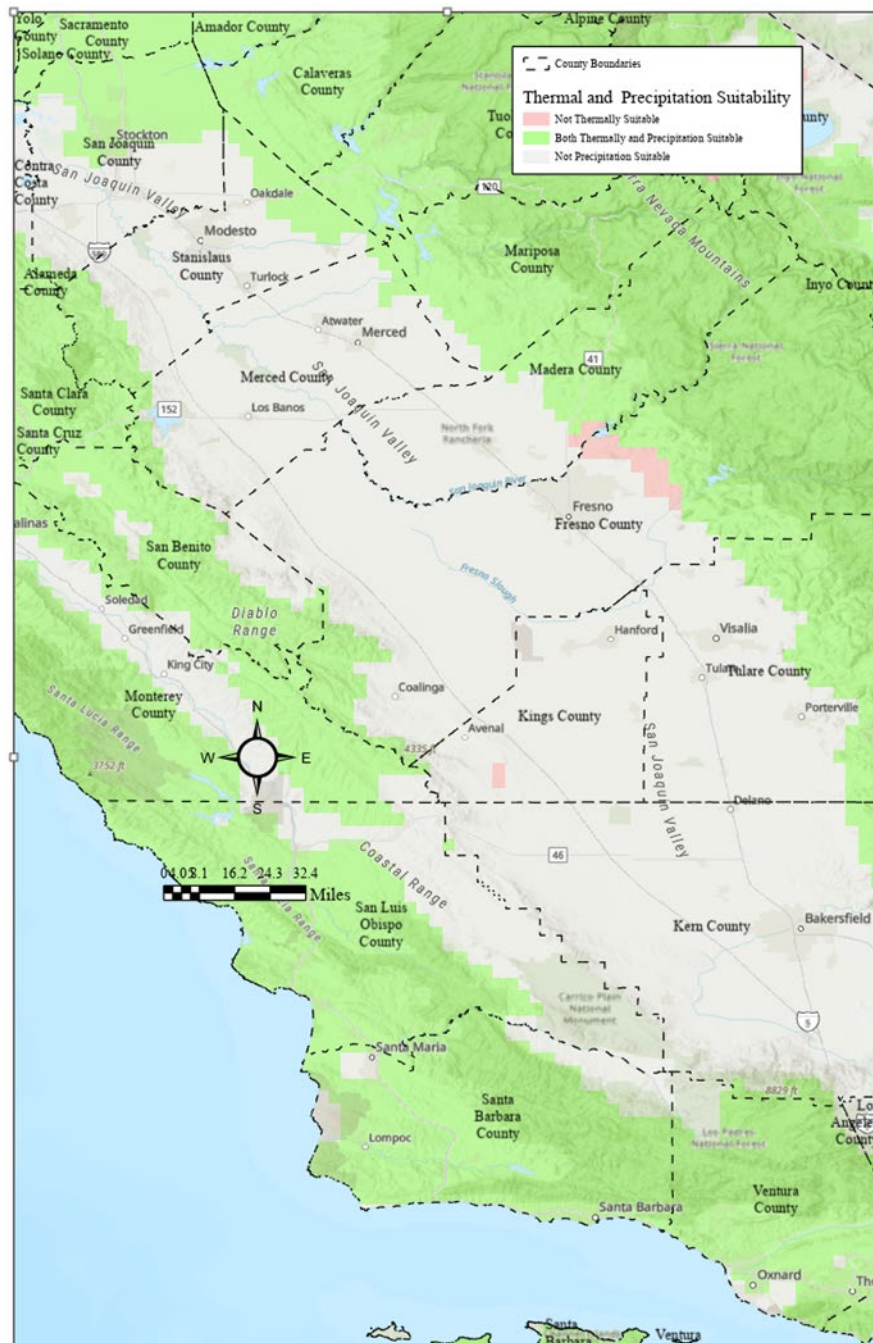


Figure 4.3. Thermal and precipitation suitability for saffron cultivation in the San Joaquin Valley, California. Pink-shaded regions indicate land areas beyond saffron's thermal tolerance limits (below -22°C or above 45°C). Green areas represent zones meeting both thermal and precipitation suitability criteria, whereas grey areas denote regions where annual precipitation is insufficient to meet saffron's water requirements.

4.5.2. Flood-Hazard Exposure

The overlay highlights trade-offs between climate suitability and hydrological vulnerability showing that while much of the valley floor is climatically favorable, flood exposure along the San Joaquin and Kings River corridors constrains near-term cultivation potential for saffron and similar high-value specialty crops. Flood hazards zones are most notable along the San Joaquin, Kings, and other major river corridors in the SJV (Figure 4.4). These overlaps illustrate the trade-off between climate suitability and hydrological vulnerability, emphasizing that portions of otherwise climatically suitable land may be at risk of flood exposure. While certain crops are well suited to flooding, including to on-farm recharge, such as alfalfa, grapes, and annual crops (Sustainable Conservation, 2023) saffron is intolerant of flooding. We note that the 100-year flood zone implies an annual risk of flooding of 1% does not take into consideration effects from climate change and hence may not be a significant deterrent relative to other factors.

San Joaquin, Stanislaus, and Merced counties contain large tracts of thermally suitable land, though several low-lying segments fall within mapped floodplains that somewhat may limit availability. In contrast, Madera, Fresno, and Tulare exhibit extensive thermally suitable zones largely outside flood-prone areas, positioning them as the core target regions for saffron introduction. Kings and Kern counties maintain narrower but contiguous corridors of suitability, particularly in upland or western valley margins where flood exposure is minimal.

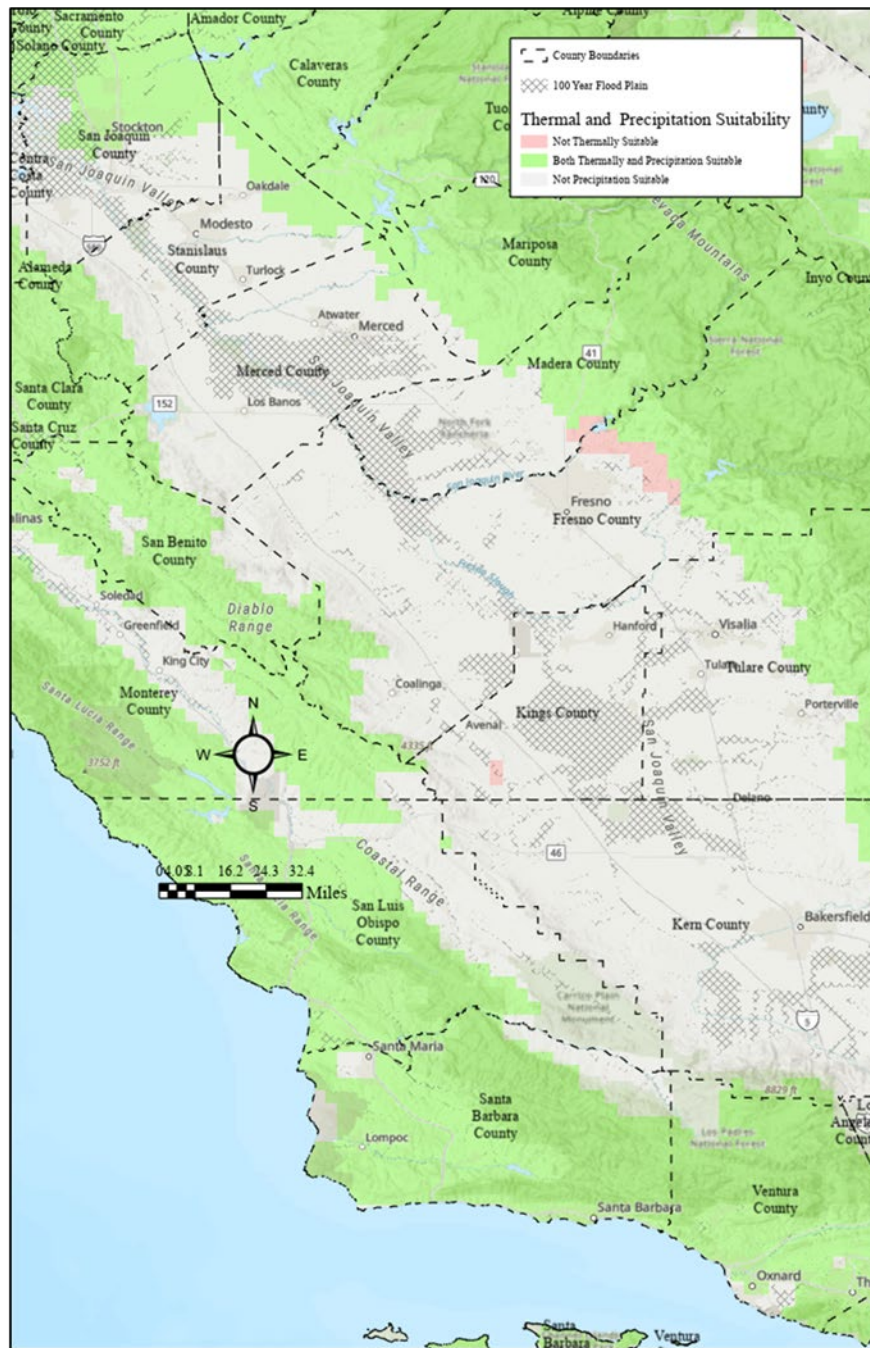


Figure 4.4. Thermal and precipitation suitability with 100-year flood-risk overlay for saffron cultivation in the San Joaquin Valley. The cross-hatched regions represent land within the Federal Emergency Management Agency (FEMA) 100-year flood zone, indicating areas with an estimated 1 percent annual inundation risk.

Overall, nearly all current agricultural land in the SJV is thermally suitable for cultivation with 5.77 million acres (Table 4.3). Fresno holds the largest total thermally suitable area (≈ 1.34 million acres). A smaller extent of agricultural land is suitable with local water (0.322 million acres), with most of this in the northernmost county of San Joaquin. The vast majority of thermally suitable land is outside of flood zones (>4 million acres).

County	Thermally Suitable Land thousand acres)	Thermally Suitable + Local Water thousand acres)	Thermally Suitable + Flood Tolerant thousand acres)
San Joaquin	630.7	256.6	327.7
Stanislaus	477.3	51.8	398.4
Merced	622.2	1.2	400.0
Madera	433.8	0.2	236.8
Fresno	1,343.2	6.4	1,085.5
Tulare	795.2	5.7	620.2
Kings	551.7	0.02	281.4
Kern	922.9	0.4	689.2
8-County Total	5,777.2	322.5	4,039.2

Table 4.3. Estimated current agricultural land that is thermally suitable for saffron, thermally suitable with local precipitation meeting water needs of saffron, and thermally suitable and outside of 100-year flood zones. Data from USDA Cropland Data Layer as of 2024 were merged with climate suitability and flood risk to estimate county acreage.

4.5.3. Feasibility of Intercropping

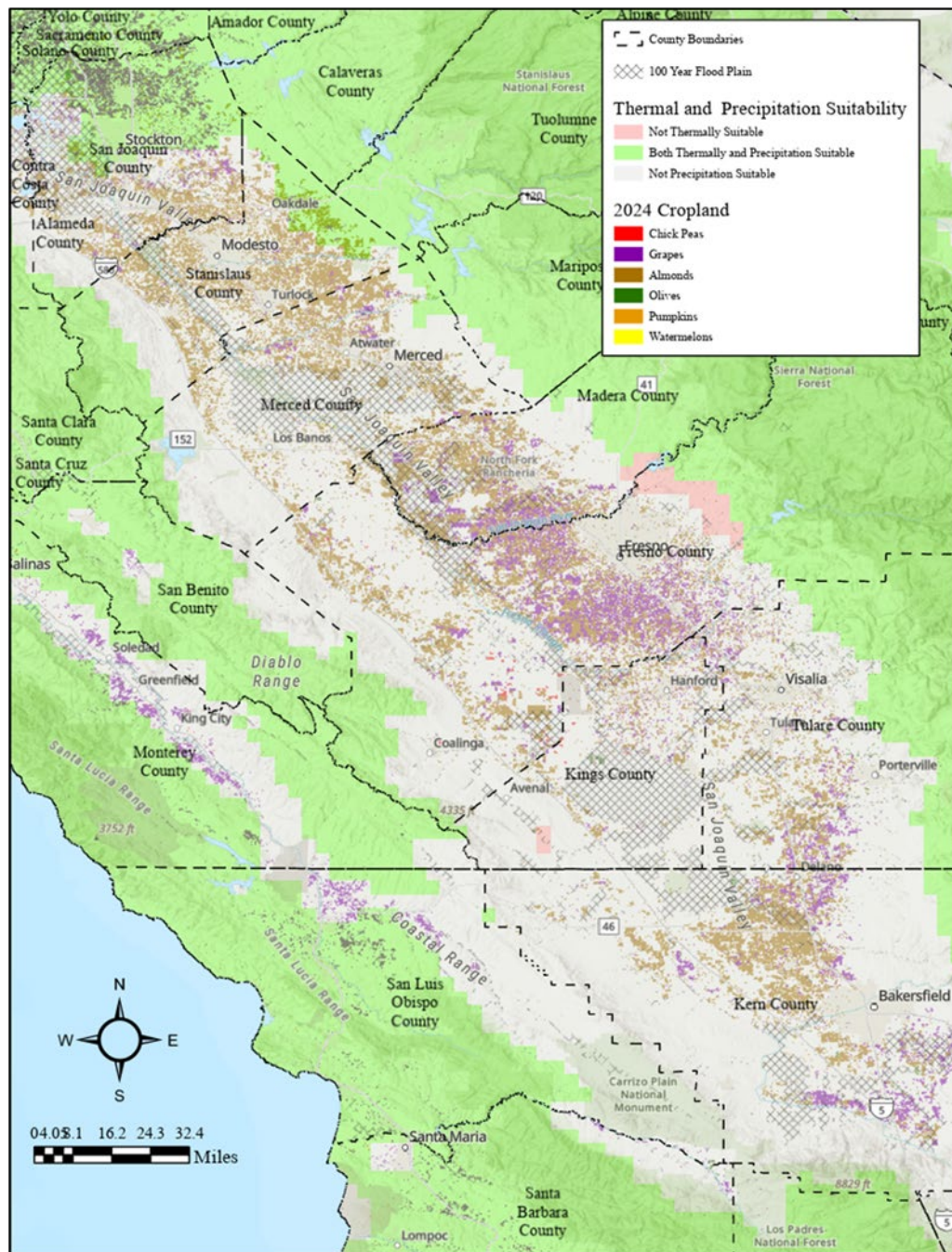


Figure 4.5. Combined saffron suitability and major crop overlays for intercropping potential in the San Joaquin Valley. This combines the climate suitability and flood risk maps with current extent of 6 potential intercropping patterns based on their 2024 distribution.

Figure 4.5 identifies intersections where existing specialty crops overlap with saffron-compatible conditions. This illustrates the geography of potential saffron intercropping could occur and emphasizes opportunities for climate-resilient intercropping strategies.

Almonds are also considered a strong intercrop partner due to their high economic return, established cultivation systems in California and intercropping cohabitation (Kumar et al., 2008). However, its management techniques and water requirements bring into question its viability concerning intercropping with saffron. Almonds are harvested mechanically, which increases the risk of physical damage to saffron corms. Secondly, excess irrigation applied for almond production may leave corms vulnerable to disease (Mirza & Kulcsar, 2025; Husaini, 2014; Koocheki, Fallahi, & Jami_Al-Ahmadi, 2020b) and some irrigation practices such as flood irrigation, may further exacerbate risks during saffron's corm integrity during the dormant period (Mirza & Kulcsar, 2025). Although their current flood and sprinkler-based irrigation practices pose challenges for saffron integration, ongoing efforts for better water efficiency and utility, such as conversion to drip and micro-irrigation systems, could mitigate excessive soil moisture and compaction, enabling almonds to evolve from a conditional to a viable intercrop under sustainable management (Peterson et al., 2022).

By contrast, crops with lower water requirements including grapes, olives, pumpkins, and watermelons reduce overall irrigation demand and support water resource allocation strategies that mitigate negative outcomes such as orchard abandonment, land fallowing, and the associated economic, social, and health consequences observed in the region (Peterson, Pittelkow, Lundy, & Collins, 2022; Ferris, 2025). Based on water requirements and management compatibility, these crops represent the most suitable companions for saffron intercropping within the San Joaquin Valley.

Chickpeas and similar legumes, while agronomically valuable for nitrogen fixation, pose challenges as intercrops with saffron. Their mechanized combine harvesting increases the risk of corm damage, and their relatively low market value further reduces their attractiveness. In California, chickpeas constitute only ~10,000 acres of cropland in the San Joaquin Valley (UC ANR, 2020a), underscoring their limited economic contribution compared to high-value specialty crops.

Crop	Water Use	Flood Tolerance	Harvest / Mechanization Compatibility	Economic Viability
Watermelon	Moderate-to-high ETc ($\approx 700\text{--}1,000$ mm yr ⁻¹)	Harvested before the onset of rain;	Mechanization limited; harvest labor-intensive.	Moderate value; annual crop with rotational benefits.
Chickpeas	Low ETc ($\approx 400\text{--}500$ mm yr ⁻¹);	Tolerance to brief inundation; well- drained fields preferred.	Combine- harvested crop;	Moderate value; rotational benefit for soil nitrogen.
Pumpkins	Moderate ETc ($\approx 500\text{--}700$ mm yr ⁻¹);	Moderate tolerance to temporary flooding.	Mechanization limited; harvest labor-intensive.	Moderate value; direct- market potential.
Almonds	High ETc ($\approx 1,200\text{--}2,400$ mm yr ⁻¹);	Moderate tolerance; requires drainage management.	Mechanized shaker harvest and wide lanes limit intercropping.	High market value
Grapes	Moderate ETc ($700\text{--}900$ mm yr ⁻¹);	Moderate tolerance: recover from short inundation if soil drains quickly.	Mechanization limited; harvest labor-intensive.	High value; strong domestic and export demand.

Table 4.4. Binary decision matrix for evaluating saffron intercropping compatibility in the San Joaquin Valley References (for Table 3): CDFA (2022); FAO (2020); Hartz (2020); Hanak et al. (2023); Husaini (2014); Koocheki et al. (2020); Peterson et al. (2022); UC ANR (2020a, 2020b, 2020c); California Department of Water Resources & University of California (2020).

Table 4 summarizes the intercrop candidate acreage and compatibility indicators across San Joaquin Valley counties. Values reflect thermally suitable and flood-safe lands for each crop (CDFA, 2022). Chickpeas, although agronomically valuable for nitrogen

fixation, occupy only 6,700 acres of non-flooded land and remain poorly aligned with saffron due to low market value and mechanical harvesting risks that threaten corm integrity (UC ANR, 2012).

Watermelon and pumpkins have moderate irrigation demands (400 to 600 mm and 400 to 450 mm, respectively) under field conditions (FAO, 2020; UC ANR, 2020). Both crops are typically grown under controlled drip or furrow irrigation systems rather than flood irrigation, and their growth cycles conclude before saffron's autumn emergence, preventing temporal or hydrological overlaps, thus avoiding negative impacts on saffron intercropping. Furthermore, these crops are harvested by hand and are not subject to logistical challenges from harvest that could impact saffron. Both crops have moderate economic value in isolation. Intercropping with saffron, using novel harvesting methods, may increase the utility of cultivation to farmers and may reduce or have positive impact upon cost due to multiple crops sharing a single resource like a shared risk strategy. This concept suggests more study involving management and markets of specific crops. Moreover, it is expected that future water utility adaptation strategies will increasingly encourage integration of low-water annuals such as pumpkins into perennial systems to preserve groundwater allocations and sustain regional employment (Peterson, Pittelkow, Lundy, & Collins, 2022).

Grapes rank as the most compatible intercropping partner for saffron within the SJV. Vineyard spacing and trellising allow unobstructed saffron growth between rows, while grape irrigation systems predominantly drip or micro-sprinkler maintain the dry-soil environment required for corm dormancy. Both crops have non-overlapping harvest calendars: saffron flowers in autumn, long after grape harvest, minimizing field congestion.

Olives demonstrate strong biophysical and operational compatibility with saffron. Their moderate water demand and deep rooting systems limit competition for surface moisture, while partial canopy shading helps reduce near-surface temperatures during summer dormancy. Olive groves typically employ micro-irrigation, minimizing saturation and fungal risk to saffron corms. Avoiding super high density olive plantings that rely exclusively on full mechanical harvest (1.5 m tree spacing, 4 m row spacing, ~4 m height) in favor of traditional or low-density systems (7–9 m tree and row spacing) that support smaller mechanized or hand harvesting and dry farming, positions olives as the second-most favorable perennial partner for climate-resilient saffron integration (Vosen, 2010; UC ANR, 2024; Santa Cruz Olive Tree Nursery, 2025).

Across the San Joaquin Valley, spatial analysis indicates broad opportunity for saffron intercropping, though total acreage and suitability vary considerably by crop and county (Table 5). Almonds dominate overall potential over twice the area of grapes—and reflecting their economic and spatial centrality under current land-use patterns. Grapes remain a strong complementary perennial with acres concentrated in Fresno, Kern, and Stanislaus Counties. Olives add approximately 9,500 acres of land, particularly in Fresno, Tulare, and Kern Counties. Pumpkins and watermelons contribute smaller but

strategically distributed acreages, roughly 2,000 and 1,100 acres respectively, aligned with reduced-tillage and efficient irrigation systems that sustain surface dryness and prevent excess moisture accumulation (Ferris, 2025).

County	watermelon	pumpkin	almond	olives	chickpea	grapes
San Joaquin	404	1306	117301	1136	13	34105
Stanislaus	270	353	271638	1088	0	5078
Merced	376	4	190382	624	107	5100
Madera	2	0	123804	110	9	39871
Fresno	4	0	333783	1103	5552	168950
Tulare	0	0	117089	4340	25	49010
Kings	1	0	56567	34	994	8100
Kern	76	0	252788	1150	0	69152
Total	1133	1663	1463352	9585	6700	379366

Table 4.5: Acres of potentially suitable existing cropland that is both thermally suitable for saffron cultivation and outside of 100-year flood zones in the 8 counties of the SJV. Derived from USA cropland data (2024).

By aligning saffron’s minimal irrigation demand with these emerging water constraints, intercropping offers the benefits of sustaining agricultural revenue, novel crop introduction and maximizing water utility. The convergence of climatic suitability, available infrastructure (such as drip and micro-irrigation systems), and economic necessity positions the southern valley as the logical testing ground for large-scale saffron integration. Together, these resource patterns underscore saffron’s role as a climate-resilient diversification crop capable of complementing existing perennial systems while supporting the broader policy objective of balancing groundwater sustainability with farm-level profitability.

4.6. Discussion and Conclusion

The climate suitability of saffron across the SJV carries important implications for the region’s agricultural future. Unlike high-value crops that are constrained by rising evapotranspiration and groundwater scarcity, saffron’s low water requirement and dormancy during the hot, dry season align well with California’s emerging water-limited conditions. These characteristics position saffron as a model for integrating novel, climate-resilient crops into existing specialty-crop systems, advancing the shift from water-intensive monocultures toward diversified, adaptive land use. As studies by Husaini (2014) and Koocheki et al. (2020) demonstrate, saffron can thrive in semi-arid climates with as little as 260 mm of annual effective water use.

Spatial analysis of the SJV reveals that nearly all major agricultural counties particularly Fresno, Kern, and Tulare contain large contiguous tracts of land where thermal and

hydrological conditions support saffron cultivation with minimal modification for the foreseeable future. While flood risk persists along riverine corridors, these zones are relatively limited compared to the broad acreage suitable for saffron. However, more investigation is suggested regarding the interaction of soil requirements and effects from sudden inundation within the central valley.

Grapes and olives emerge as the most compatible companion crops examined here qualitatively. Current cultivation practices combine efficient drip-irrigation systems, gentle harvest practices, and root-zone separation that limits moisture competition (Hartz, 2020). Short season crops such as pumpkins and watermelons further expand diversification opportunities, enabling smallholders to optimize land use through staggered cropping cycles that maintain economic output while reducing total water withdrawals (Ferris, 2025; UC ANR, 2020b,c). However, actual trials of intercropping are needed to assess both operation logistics and impacts to yield and quality. Other high-value low-water crops exist such as agave, amaranth and/or quinoa and prickly pear cacti. Yet, more investigation is needed regarding their intercrop capability, market appeal and capacity.

Beyond its agronomic feasibility, saffron's introduction addresses three strategic dimensions critical to the Valley's resilience. First, its low water use enables profitability on parcels that might otherwise face less desirable choices such as fallowing due to increased cost. Second, its market versatility spanning culinary, textile, and nutraceutical/pharmaceutical sectors, diversifies revenue streams and stabilizes farm incomes (FAO, 2020). Third, saffron's adaptability to a wide range of soil textures and temperature regimes allows targeted integration into areas most affected by drought and groundwater decline, providing a transitional crop model for regions under hydrological constraint (Hanak et al., 2023; Shahandeh, 2020; De Feudis et al., 2025).

Labor intensity remains the principal constraint to widespread adoption. Harvesting and processing are still largely manual, requiring significant time investment relative to other specialty crops; however, emerging mechanization technologies and automation research are expected to alleviate this barrier (Saeidirad, 2020). Pilot automation studies in Iran and Spain demonstrate prototype robotic separators reducing harvest time by 35-50 percent (Saeidirad, 2020), indicating early feasibility for scaled trials within California's specialty-crop sector.

Recent USDA priorities have emphasized strengthening domestic production through the "Grown in America" initiative. Research on emerging crops such as saffron naturally supports this broader agenda by identifying climate-resilient, high-value options that can be cultivated within U.S. agricultural systems. Collectively, this study situates saffron within a practical framework for adaptation and transition. Its integration into perennial and short-season systems demonstrates how spatial analysis can inform field-level diversification and regional investment planning. The findings reinforce that climate-suitable, low-water, high-value crops such as saffron are central to sustaining the SJV's agricultural viability in the decades ahead.

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CHAPTER 5: CONCLUSION

5.1 Introduction

California's San Joaquin Valley (SJV) stands at a pivotal crossroads. Decades of intensive cultivation, coupled with climate warming and progressive groundwater depletion, have transformed one of the world's most productive agricultural regions into a landscape increasingly defined by scarcity. Yet, as demonstrated throughout this dissertation, innovation and system-level management provide a credible pathway toward a more sustainable and economically resilient future for California agriculture. By examining three high-value specialty crops, coffee, olives, and saffron, this research identifies viable adaptation strategies that integrate climatic suitability, agronomic feasibility, and water-resource governance under expected state climatic conditions. Each crop contributes unique lessons for adaptation within California's evolving climate system: coffee reveals the expanding potential of subtropical perennials as minimum winter temperatures rise along coastal zones; olives illustrate how Mediterranean perennials align with water utility strategies of driven irrigation efficiency and mechanization; and saffron demonstrates a low-water, high-value diversification strategy capable of stabilizing income on acreage facing groundwater curtailments. Collectively, these findings confirm that climate-smart diversification is not theoretical but operationally achievable across California's agricultural mosaic.

Geospatial and economic analyses confirm that California contains extensive tracts of existing agricultural land capable of supporting climate-smart diversification under near-term climate scenarios. Adaptation opportunities form a north-south gradient across the state: coastal counties such as Santa Barbara, Ventura, San Luis Obispo, and Monterey are most suitable for coffee; mid-valley counties including San Joaquin, Stanislaus, Merced, Madera, Fresno, Tulare, and Kern demonstrate strong compatibility with olives; and central and southern valley zones—notably Fresno, Madera, Merced, Tulare, Kern, and Stanislaus—offer high potential for saffron integration on marginal or fallowed acreage.

This spatial complementarity underscores that adaptation should be approached as a portfolio strategy rather than a one-to-one crop substitution. Each crop occupies its own ecological and economic niche within California's climatic mosaic, creating a network of production systems optimized for temperature, water, and market alignment. Within the framework of water utility strategy, such diversification mitigates the economic and social impacts of groundwater-use reductions by enabling growers to transition from high-consumptive crops toward lower-ET, high-value alternatives.

At a strategic level, this system's perspective defines the dissertation's center of gravity: resilience emerges not from any single crop but from the deliberate integration of multiple complementary systems. In contrast to monocropping, which concentrates environmental and market risk within a narrow set of conditions, diversified systems

distribute vulnerability across climate zones and economic sectors. By aligning climate-suitable production zones, technological innovation, and market positioning, California agriculture can redistribute risk while sustaining regional livelihoods. This approach reframes adaptation as a dynamic management strategy; one that connects on-farm decisions with long-term groundwater sustainability, rural stability, and policy innovation under expected future climatic conditions

5.2 Technology, Mechanization, and Innovation

Long-term adoption of diversification strategies in California agriculture will depend heavily on mechanization, automation, and precision water management. While saffron remains one of the most labor-intensive specialty crops, recent advances in semi-mechanized harvest systems and improved soil-handling techniques have begun to reduce the need for manual labor (Saeidirad 2020). Drone-based canopy monitoring, sensor-driven irrigation scheduling, and AI-assisted data integration—technologies already emerging through many entities such as University of California's Center for Information Technology Research in the Interest of Society (CITRIS) and partner institutions extend similar efficiencies to olive and coffee production systems

Innovation is equally essential across the value chain. Cooperative processing facilities, regional branding initiatives, and local certification programs can help translate on-farm efficiency gains into stronger financial performance for small and mid-sized growers.

These innovations collectively represent a shift from reactive adaptation to proactive agricultural design. Through mechanization, digital monitoring, and cooperative marketing, California producers can enhance productivity, conserve water, and maintain competitiveness while aligning with the state's broader sustainability and equity objectives. Building on these technological and organizational advances, the next challenge lies in translating efficiency and sustainability gains into market value. Effective branding, certification, and supply-chain coordination serve as the outward expression of the same systems thinking that drives innovation at the field level.

5.3 Markets, Branding, and Global Positioning

Market competitiveness remains a decisive factor in the long-term viability of climate-smart diversification. The global specialty-crop marketplace rewards both product quality and verified origin, making branding, traceability, and certification systems essential components of economic sustainability. Within this context, olives and saffron represent near-term commercial opportunities, while coffee defines an emerging frontier market whose expansion will depend on future innovation and consumer perception.

The U.S. olive-oil industry reached an estimated USD 3.1 billion in 2024 and is projected to grow by more than 7 percent annually through 2030 (Grand View Research 2024). Despite this growth, the European Union continues to dominate global trade, exporting roughly 252 000 tons of olive oil each year valued at approximately € 1.2 billion (≈ USD

1.31 billion) primarily from Spain and Italy (International Olive Council 2025). California producers therefore compete in a market shaped by EU subsidies, geographic-indication labeling, and deeply established consumer loyalty.

To achieve parity, California growers must strengthen strategic branding, authenticity certification, and supply-chain transparency that highlight domestic quality while communicating environmental advantages. Linking verified origin labeling with water-efficient and carbon-smart production practices can position California specialty crops as premium, sustainable alternatives to imported goods (Hanak et al. 2019).

Saffron presents a similar opportunity on a smaller scale. Developing a unified “California-grown saffron” brand supported by cooperative processing, regional marketing, and consistent quality standards could help offset the dominance of imported saffron from Iran and Spain. Coffee, though currently limited to coastal microclimates, benefits from niche branding rooted in innovation, provenance, and regenerative agricultural practices, positioning it alongside California’s craft-beverage and specialty-crop sectors.

These branding and certification frameworks extend beyond marketing strategy; they reinforce the economic rationale for utility of water resource through aligned diversification by ensuring that water-efficient production systems remain profitable under restricted water allocations. Integrating market strategy with mechanization, cooperative processing, and supportive policy incentives will determine whether these specialty crops remain niche enterprises or evolve into commercially significant pillars of California’s agricultural economy.

Crop	Water Need (ETc, mm)	Thermal Range (°C)	SGMA Alignment	Economic Value	Mechanization Feasibility	Overall Adaptation Potential	Representative Counties / Cultivation Regions
Coffee (<i>Coffea arabica</i>)	900–1200	15–32	Conditional (requires shade + precision irrigation)	Very High	Developing	Emerging	Santa Barbara, Ventura, San Luis Obispo, Monterey (Coastal zones)
Olive (<i>Olea europaea</i>)	300–800	5–40	Strong (established micro-irrigation, perennial root system)	High	High	Proven	San Joaquin, Stanislaus, Merced, Madera, Fresno, Tulare, Kern

Crop	Water Need (ETc, mm)	Thermal Range (°C)	SGMA Alignment	Economic Value	Mechanization Feasibility	Overall Adaptation Potential	Representative Counties / Cultivation Regions
							(SJV corridor)
Saffron (<i>Crocus sativus</i> L.)	≈ 260	–22 to 45	Excellent (dormant in dry season, low ETc)	Very High	Developing	Excellent	Fresno, Madera, Merced, Tulare, Kern, Stanislaus (SJV intercropping zones / fallowed acreage)

Table 5.1 Derived from Hanak et al. (2023); Husaini (2014); Koocheki et al. (2020); Peterson et al. (2022); USA Cropland (2024) DaMatta & Ramalho, 2006 Wintgens, 2012. Parker and Abatzoglou 2017. Comparative Climate, Agronomic, and Regional Attributes of Model Crops in California (ETc = Crop Evapotranspiration; SGMA = Sustainable Groundwater Management Act)

5.4 Synthesis of specialty crop viability in the San Joaquin Valley

Regional Applicability of Saffron within the San Joaquin Valley

Saffron demonstrates broad climatic and agronomic suitability across the entire San Joaquin Valley (SJV), extending from San Joaquin and Stanislaus Counties in the north through Merced, Madera, Fresno, Tulare, Kings, and Kern Counties in the south. The region's Mediterranean climate characterized by cool winters, hot dry summers, and low evapotranspiration demand closely aligns with saffron's growth cycle. Existing drip- and micro-irrigation infrastructure developed for orchard and vineyard systems can be readily adapted for saffron production, particularly on fallowed or deficit-irrigated parcels targeted under SGMA transition plans.

However, localized site selection remains critical. Areas subject to periodic flooding, poor drainage, or salinity accumulation especially in western Tulare, Kings, and southern Fresno Counties require mitigation measures such as raised beds, soil amendments, or controlled drainage systems. When these management practices are implemented, saffron offers a low-water, high-value diversification pathway applicable to nearly all SGMA-affected counties of the SJV, reinforcing its role as a cornerstone option for climate-resilient specialty-crop development in California.

Coffee Cultivar Scope and Future Investigation

While this study focused exclusively on *Coffea arabica*, which exhibits relatively narrow climatic tolerances, other cultivars such as *C. canephora* (robusta) or emerging hybrid lines may offer improved adaptability to heat and water stress. These alternative genotypes could, in theory, extend cultivation potential into warmer or more arid microclimates that are currently marginal for Arabica including limited foothill zones bordering the San Joaquin Valley. However, future field-based and physiological investigations are required to evaluate yield stability, irrigation feasibility, and market quality under California conditions before any broad-scale conclusions can be drawn, although regarding the SJV region it is very unlikely that large scale operations could be supported climatically.

Oil Olive

Olive oil production is viewed a “stable” commodity for the SJV region and other areas in California. It should be noted that U.S. production efforts are hindered by two factors: (1) cost, particularly labor, and (2) limited consumer education regarding commodity attributes (University of California ANR 2024; Wang, Moscatello & Flynn 2013; Chrysochou, Tiganis, Trigui, & Grunert 2022). These constraints result in higher-priced oils with limited distribution, based on manual harvesting for higher quality. This study however focuses primarily on Arbequina whose characteristics support climate and

phenological suitability, farm-management needs, and market considerations that promote higher volume. Within this context, a debate persists regarding quality versus quantity, which it is theorized can be addressed through improved consumer awareness involving health benefits and quality along with local production aspects. The combination of present climate-change effects upon traditional European/Mediterranean growing regions, recent political/economic discord combined with an aggressive consumer awareness education, should strengthen support for “Grown in America” olive oils.

5.5 Limitations and Future Work

This dissertation necessarily simplifies the complexity of California’s agro-ecosystems. While the modeling framework integrates climate, hydrology, and agronomic parameters at high spatial resolution, certain assumptions particularly those regarding soil heterogeneity, microclimatic variation, and market volatility introduce uncertainty into regional suitability estimates. Future studies should incorporate higher-resolution microclimate and soil datasets to refine spatial predictions and improve the precision of county-level adaptation planning.

The climate scenarios analyzed here emphasized moderate-warming trajectories; however, higher-emission pathways could substantially alter temperature and water-availability envelopes for all three crops. Expanding the analysis to include these trajectories would better quantify long-term resilience thresholds and inform adaptive irrigation scheduling under extreme conditions.

Field-level validation is equally essential. While modeled suitability and evapotranspiration (ET_c) values align with published field data, multi-year experimental trials are needed to evaluate yield stability, pest dynamics, and water-use efficiency under real management regimes. Collaborations among universities, growers, and state agencies should advance this work by converting modeled insights into operational decision-support tools that guide Groundwater Sustainability Agencies (GSAs) and Resource Conservation Districts (RCDs) in crop-transition planning.

Economic and social dimensions also warrant deeper investigation. The economic modeling in this dissertation emphasizes water-use efficiency and market value but does not explicitly evaluate labor dynamics, equity considerations, or financing constraints faced by small and socially disadvantaged farmers. Future research should integrate these socio-economic factors into decision frameworks to ensure that diversification enhances inclusion as well as resilience.

Finally, the potential for alternative coffee cultivars and hybrid saffron or olive varieties underscores the importance of continued plant-breeding and physiology research tailored to California’s semi-arid conditions. Long-term success will depend not only on identifying climate-suitable species but also on building adaptive institutions and

technologies capable of sustaining them under future climate-policy mandates to include governance concerns such as SGMA.

5.6 Outlook

The findings of this dissertation underscore that California's agricultural transformation will depend on strategic diversification, technological adaptation, and policy alignment. By linking climate modeling, agronomic feasibility, and economic valuation, this work demonstrates that resilience and profitability are not mutually exclusive. The case studies of coffee, olives, and saffron collectively illustrate how climate-smart cropping systems can balance water sustainability, market opportunity, and social equity. Continued research, field validation, and institutional support will determine whether these concepts evolve from academic modeling to practical implementation across the San Joaquin Valley and coastal California. If executed strategically, diversification of this kind can preserve California's agricultural legacy while establishing a model of climate-adaptive production for semi-arid regions worldwide.

5.7 References

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