UC Merced

UC Merced Electronic Theses and Dissertations

Title

Climate Change Impacts on Agriculture Water Dynamics and Conservation in San Joaquin Valley of California

Permalink

https://escholarship.org/uc/item/9k7887hx

Author

Kandhway, Anshika

Publication Date

2024

Peer reviewed|Thesis/dissertation

eScholarship.org Powered by the California Digital Library
University of California

UNIVERSITY OF CALIFORNIA, MERCED

Climate Change Impacts on Agriculture Water Dynamics and Conservation in San Joaquin Valley of California

DISSERTATION

submitted in partial satisfaction of the requirements

for the degree of

DOCTOR OF PHILOSOPHY

In Environmental Systems

by

ANSHIKA KANDHWAY

Dissertation Committee:

PROFESSOR MARTHA CONKLIN, ADVISOR, CHAIR

PROFESSOR SAFEEQ KHAN, ADVISOR

PROFESSOR JOHN ABATZOGLOU

PROFESSOR JOSUE MEDELLIN-AZUARA

Summer 2024

© 2024 ANSHIKA KANDHWAY

The dissertation of Anshika Kandhway, titled Climate Change Impacts on Agriculture Water Dynamics and Conservation in San Joaquin Valley of California is approved:

Professor John Abatzoglou

Professor Josue Medellin-Azuara

Professor Safeeq Khan (Faculty Advisor)

Professor Martha Conklin (Faculty Advisor)

To my family and friends
for their constant support and unconditional love. I love you all dearly.

TABLE OF CONTENTS

LIST OF FIGURES ..... **VI**
LIST OF TABLES ..... **VIII**
ACKNOWLEDGMENTS ..... **IX**
ABSTRACT OF THE DISSERTATION ..... **X**
1. CHAPTER 1: INTRODUCTION **1**
1.1. Background 1
1.2. Research gap and questions 3
1.3. Scientific contribution 4
1.4. References 5
2. CHAPTER 2: WATER USE DYNAMICS OF ALMOND AND PISTACHIO CROPS IN THE MEDITERRANEAN REGION AMID CLIMATE CHANGE **8**
2.1. Abstract 8
2.2. Introduction 8
2.3. Methods 11
2.4. Results 15
2.5. Discussion 25
2.6. Conclusion 30
2.7. References 31
3. CHAPTER 3: RISING AGRICULTURE WATER DEMAND AND SUPPLY GAP IN SAN JOAQUIN VALLEY OF CALIFORNIA **39**
3.1. Abstract 39
3.2. Introduction 39
3.3. Methods 41
3.4. Results 45
3.5. Discussion 50
3.6. Conclusion 55
3.7. Reference 56
4. CHAPTER 4: EVALUATING WATER CONSERVATION UNDER ALTERNATE LAND USE AND CLIMATE CHANGE SCENARIOS IN SAN JOAQUIN VALLEY, CALIFORNIA **65**
4.1. Abstract 65
4.2. Introduction 65
4.3. Methods 68
4.5. Results 72
4.6. Discussion 76
4.7. Conclusion 81
4.8. References 82
5. CHAPTER 5: CONCLUSION **88**
APPENDICES **90**
Appendix A: Supplemental Information for Chapter 2 90
Appendix B: Supplemental Information for Chapter 3 100
Appendix C: Supplemental Information for Chapter 4 108
..... 110

LIST OF FIGURES

Figure 2.1 Panel A shows study domain of San Joaquin Valley in California. Circles represent calibration (Ca & Cp; where "a" represents almond and "p" represents pistachio) and validation (Va & Vp) sites of eddy covariance flux stations providing daily observed ET values. Panels B and C show the grid locations with ≥10% of the grid area under almond (B) and pistachio (C) crops per USDA, 2020 data. 11

Figure 2.2 Comparisons of modeled ETc with observations from eddy fluxes and CIMIS estimations. A: (top panels): Scatter plot of observed evapotranspiration from Ameriflux eddy covariance flux-tower sites in almond and pistachio orchards versus modeled ETc. B. (bottom panels) Scatter plot of ETc estimations from spatial CIMIS versus modeled results showing yearly average of daily ETc during 2011-2020 years over all grids of respective crops. Horizontal and vertical bars represent one standard deviation in space for both data sources. 17

Figure 2.3: Spatial pattern of days to accumulate chill hours for almond (a: RCP4.5; b: RCP8.5) and pistachio (c: RCP4.5; d: RCP8.5) under baseline and climate change scenarios. The forced grids percentage is the average percentage of crop grids that need to be forced for meeting chill hours requirements for successful bud breaks in the next year during the ten-year period. 19

Figure 2.4: Spatial pattern of maturity period (between flowering to maturity days) for almond (a: RCP4.5; b: RCP8.5) and pistachio (c: RCP4.5; d: RCP8.5) under baseline and climate change scenarios. 20

Figure 2.5: Daily transpiration fluxes by months showing the average of baseline (blue), warming-only (magenta), and warming + eCO2 (green) scenarios in RCP4.5 and RCP8.5. Shaded area and numbered points on the x-axis denote traditional baseline phenology dates for the main stages: 1: Flowering, 2: Peak LAI, 3: Harvest, and 4: Dormancy..... 21

Figure 2.6: Decadal average of daily ETc over the active growing season (i.e., total yearly ETc divided by number of days with LAI>0) under three climate and two CO_2 scenarios for almonds and pistachios. Colored bars show average values and black error bars show one standard deviation from the mean baseline..... 23

Figure 2.7: Average annual ETc difference from the baseline at decadal period. . 25

Figure 3.1: Study area map showing SJV boundary (black) with location of 7 crops within the hydrologic regions of San Joaquin (north) and Tulare Lake (south) basins (blue). 43

Figure 3.2:Crop water demand change from baseline. Difference between the total cumulative ETc from baseline and climate change scenarios for each crop in early, mid and late periods under RCP4.5 and RCP8.5. Average is the area weighted average for each crop in each grid, summarized for the whole SJV. 47
Figure 3.3: Monthly demand from SJV and combined surface water supply from two basins. The brown and dark red lines represent monthly the demand in the water year for baseline and climate change periods (early, mid late) and two emission scenarios (RCP4.5 and RCP 8.5). For all panels grey and blue lines represent the monthly supply. The shaded regions is the standard deviation showing yearly variation for given months and time periods. 48
Figure 3.4: Monthly demand from portion of SJV falling in San Joaquin and Tulare Lake basins and monthly surface water supply from each of two basins. The grey and dark red lines represent monthly the demand in the water year for baseline and climate change periods (early, mid late) and two emission scenarios (RCP4.5 and RCP 8.5). The dark grey and blue lines represent the monthly supply.....49

Figure 4.1: Map of study area showing SJV domain of study (black boundary) and delineated desert boundary in California (dark grey). Coloured regions in the SJV domain represents location of seven main crops.....68
Figure 4.2: Estimation of ETc from VIC-CropSyst model, Spatial CIMIS, VIIRS and OpenET products. The box and violin plot represents median, interquartile range and variation in space. 72
Figure 4.3: Average water demand under 5 land use and 2 climate change scenarios. HBF: suitable habitat areas with fallowing history, HBNF: suitable habitat areas with no fallowing history, GWRP: suitable habitat sites with good to excellent groundwater recharge potential, and SDP: suitable habitat sites with solar development potential.....73
Figure 4.4: Water demand reduction from the baseline water use by each crop under 4 land use scenarios in RCP 8.5. HBF: suitable habitat areas with fallowing history, HBNF: suitable habitat areas with no fallowing history, GWRP: habitat sites with good to excellent groundwater recharge potential, and SDP: habitat sites with solar development potential.....74
Figure 4.5: Water demand reduction (in acre-feet per acre) by each crop under four land use scenarios in RCP8.5. HBF: suitable habitat areas with fallowing history, HBNF: suitable habitat areas with no fallowing history, GWRP: habitat sites with good to excellent groundwater recharge potential, and SDP: habitat sites with solar development potential.....75

LIST OF TABLES

Table 2.1:Model calibration and evaluation results. a. Observed and modeled median developmental phenological stages' dates (DOY in parentheses) for almond and pistachio crops. b. Model performance using the goodness of fit models against observed daily ETc over calibration and validation sites of eddy covariance flux-tower. Validation results against daily ETc Spatial CIMIS (CIMIS) estimations over all grids of respective crops. 16

Table 2.2: Summary of dates (DOY) to start phenological stages and active period duration (days) in baseline and their relative changes in climate change scenarios. 18

Table 2.3: Average daily ETc (mm/day) with 2 standard deviations (within parentheses) for almond and pistachio crops for baseline and climate change scenarios. The SD values of daily ETc represent variations in both time and space dimensions. 22

Table 2.4: Average cumulative ETc in baseline and relative differences in climate change scenarios. 24

Table 4.1: Average ET, area and volumetric demand under five land use scenarios and two climate change scenarios. Volumetric demand is calculated by multiplying ETc with area under each land use. 75

Table 4.2: Overview of land repurposing strategy uses, benefits, drawbacks, challenges, potential solutions, beneficiaries, case studies and references. 78

ACKNOWLEDGMENTS

Most of all, I would like to express my deepest gratitude to Professor Martha Conklin and Professor Safeeq Khan for the opportunity they gave me, for their support, and invaluable guidance throughout my academic journey. I would like to thank the members of my dissertation committee Josue Medellin-Azuara and John Abatzoglou for their advice and expertise were invaluable to my development as a scientist. I would like to thank Professor Jennifer Adam for her valuable guidance and support. A special thanks to my friend and guide, Dr. Fabio Scarpare, for his patience and support throughout my research. I would like to thank Dr. Mingliang Liu and Mr. Roger Nelson at Washington State University for their support and collaboration.

I also extend my sincere gratitude to the faculty members and staff of the Environmental System program for providing me with an amazing academic environment. A special thanks to the Mountain Hydrology group, present and past members. Thanks for the fun and support. I want to express my heartfelt gratitude to my friends, at UC Merced including Stefano, Saswata, Swadha, Megha, Arya, Subhaya, Shubham, Aliva, Han, Naivy, Elena, Norm and many more. This journey was awesome with all of you around. A special thank you to Arshdeep, my life partner and best friend, for his patience, understanding, and inspiration. Finally, but not least, I want to thank my parents Rajkumar Ram, Sumitra Devi, my siblings Akanksha, Ekta, and Ankit, all the rest of my family. Special thanks to my sister Riya for her immense support, my friends Kritika, Anuj, Antara, Taruna and all my friends from India. The most difficult part of this Ph.D. was being far away from all of you. Thank you all. This research was supported by USDA National Institute of Food and Agriculture (grant 2018-67004-24705) and through a grant from Fresno-Merced Future of Food Innovation (F3) Initiative.

ABSTRACT OF THE DISSERTATION

Climate Change Impacts on Agriculture Water Dynamics and Conservation in San Joaquin Valley of California

by

Anshika Kandhway

Doctor of Philosophy in Environmental Systems

University of California, Merced, 2024

Professor Martha Conklin, Chair

The multi-billion-dollar agriculture industry of California's San Joaquin Valley relies heavily on irrigation, which is influenced by hydro-climatological processes varying across time and space. This sector faces significant challenges in water availability due to droughts, regulatory changes, and land conversions, which are expected to worsen with climate change. These factors create uncertainties in understanding future water demand, availability, and resource planning. There is a need for a comprehensive examination of the combined effects of climate change and elevated CO_2 on understudied crops, the seasonal variability in water demand and supply, and the long-term impacts of land repurposing on water conservation. This dissertation addresses these uncertainties and fills research gaps related to the impact of climate change on agriculture and water management in the region. The research first explores how climate change and elevated atmospheric CO2 affect water use and phenology in almonds and pistachios, two significant water-consuming yet understudied crops. The results suggest notable changes in phenology, irrigation needs, and reveal their vulnerabilities to climate change. Next, the study scales to seven major crops to investigate the future water demand-supply gap in SJV agriculture at basin scales. The outcomes reveal a widening demand-supply gap for water during critical crop growth stages, particularly highlighting the susceptibility of perennial crops, and emphasizing the need for basin-scale management strategies. Finally, the research evaluates proposed conservation strategies through land repurposing under climate change scenarios. The findings demonstrate the effectiveness of land repurposing strategies in reducing water demand, with habitat restoration and groundwater recharge showing the highest potential for water savings, particularly for perennial crops like almonds. Future studies may explore long-term impacts and economic implications of the proposed adaptive strategies, including the integration of advanced irrigation technologies and crop selection based on climate resilience. These studies provide a comprehensive understanding of how climate change will affect water use in SJV agriculture and provide insights for developing adaptive strategies to implement sustainable water management and agricultural productivity in the region.

Curriculum Vitae

Anshika Kandhway

PhD. Candidate, Environmental Systems | Department of Civil and Environmental Engineering

University of California, Merced | M: +1 209-500-9161

E: akandhway@ucmerced.edu; anshikakandhway@gmail.com | linkedin.com/in/anshika-kandhway

Education

PhD. Environmental Systems, University of California, Merced, CA
2019-Ongoing

M.Sc. in Environmental Science and Resource Management, TERI University, New Delhi
2014-2016

B.Sc. (Hons.) Chemistry, University of Delhi, New Delhi
2011-2014

Research Experience

PhD. Dissertation at University of California, Merced
2019-Ongoing
Title: Impact of climate change on San Joaquin Valley agriculture
The goal is to illustrate the impact of warming and elevated CO_2 on irrigation water demand and yield of main crops grown in the San Joaquin Valley under downscaled climate change scenarios by integrating a dynamic crop growth model with a macroscale hydrology model.

Academic project at University of California, Merced
2020
Title: Newman constructed treatment wetland water budget.
A detailed estimation of the water budget information for Miller Ditch (MD), in Newman City, that will potentially be treated in a future constructed treatment wetland and reapplied on City agricultural land.

M.Sc. Thesis at The Energy and Resource Institute (TERI), *New Delhi*
2016
Title: Estimation of sediment yield of Rapti river basin using remote sensing and GIS.
Estimation of sediment yield from Rapti river using GIS based hydrological models, Universal Soil Loss Equation model and statistical tools to deduce hotspots yielding high sediment.

Academic project at National Institute of Hydrology, New Delhi
2015
Title: Material Flow Analysis (MFA) for water conservation: A case study of Ganga River Basin
Developed a Material Flow Analysis model using STAN software for the water and wastewater flows in the systems for selective processes. Integrating the model with Principal Component Analysis to prioritize contamination source in various sewage collection streams.

Academic project at TERI University, New Delhi
2015
Title: Water quality analysis of wetlands at biodiversity park and bird sanctuary
Laboratory study of vital physio-chemical and biological parameters of water quality to trace their probable sources and impact on ecosystem.

Academic Appointments and Work Experience

Graduate Student Researcher, University of California, Merced

USDA-NSF funded Innovations at the Nexus of Food, Energy and Water Systems (INFEWS) grant: Sustaining California's Food production through integrated Water and Energy Management 2021-2022

Fresno-Merced Future of Food (F3) Innovation project: California's Water for Farms: Irrigation Decisions and Climate Adaptation Strategy
2021-Present

Teaching Assistant, University of California, Merced

Environment in Crisis, Laboratory August-December 2019, 2020

Environmental Engineering Chemistry, Laboratory
January-May 2020

Engineer, Triveni Water Institute, Confederation of Indian Industry, New Delhi

July 2016-August 2018

- Co-in-charge of hydrological evaluation projects and water security plans.

- Water resource assessments of watersheds at various geographical units from micro (village level) to macro (district/state level) watersheds in varied terrains (alluvium, hard rock etc.) of India using hydrological modeling based in Geographical Information System (GIS), Remote Sensing tools.

- Community and stakeholder engagement to understand the local challenges and devising apposite strategies to mitigate them using primary surveys, community facilitated measurements and technical workshops.

- Water and soil quality assessment during field surveys and secondary data by national and local authorities.

- Climate data analysis and interpretation – summarizing and statistical analysis rainfall and temperature daily gridded data using data analyst tools for whole India.

- Water Security Plans for distilleries and bottling units of beverage industry.

Publication and Conference Papers

Kandhway, A., Scarpare, F, Liu M., Nelson R., Adam J. C., Anderson, R. G., Conklin. M. H, Safeeq M. (2024) Water Use Dynamics of Almond and Pistachio Crops in the Mediterranean Region Amid Climate Change. *Agriculture Water Management* (under review).

Kandhway, Anshika, et al. "Climate change impacts on consumptive water use and yield by almond and pistachio crops in the San Joaquin Valley, California." *Fall Meeting 2022, San Francisco, 2023*.

Kandhway, Anshika, et al. "Quantifying climate change impacts on crops growing in Merced, California." *2023 CUAHSI Biennial Colloquium, CUHSI, 2023.*

Kandhway, Anshika, et al. "Quantifying Climate Change Impacts on Water Use and Yield of Almond and Pistachio Crops in the San Joaquin Valley." *Fall Meeting 2022, Chicago, 2022*.

Fan, Qin; **Kandhway, Anshika**, et al. "California's Water for Farms: Irrigation Decisions and Climate Adaptation Strategy." *Ag Robotics Forum. USA FIRA, Fresno, 2022.*

Kandhway, Anshika and Goyal V.C. "Material Flow Analysis (MFA) for Water Conservation." *Indian Conference on Life Cycle Management. Federation of Indian Chambers of Commerce and Industry (FICCI), New Delhi, 2015.*

Technical Reports

Kandhway, Anshika; Khan, Safeeq. California's Water for Farms: Irrigation Decisions and Climate Adaptation Strategy. University of California. 2023.

Morales, Naivy, D. R.; Beutel, Marc; **Kandhway, Anshika**; Zuber, Cameron. *Newman Constructed Treatment Wetland Water Budget Report (Memorandum 2)*. University of California, Merced, 2020.

Awards and Fellowships

2023 Outstanding Student Presentation Award, AGU Fall Meeting 2023

2020 Environmental Systems Summer Fellowship, University of California

2022-23 Graduate Student Professional Development Fellowship, University of California

Conferences & Workshops

Attendee. NASA Applied Remote Sensing (ARSET) training on Biodiversity Applications for Airborne Imaging Spring 2023.

Attendee. Science Communication Workshop Spring 2023, UC Merced.

Attendee. University of California Carpentries Fall 2022 Workshop: Introduction to R, Python and Git

Attendee. Ag Robotics Forum. USA FIRA, Fresno, October 18-22, 2022.

Attendee. Fall Meeting 2022 by American Geophysical Union, Chicago, December 12-15, 2022.

Attendee. Dissertation Bootcamp, UC Merced Summer 2022.

Attendee. Introduction to ArcGIS Story Maps workshop, UCANR Informatics and GIS Statewide Program, 2021.

Organizer. Paper and Pulp Conference by Confederation of Indian Industry, New Delhi, July 27, 2018.

Organizer. 3rd Indian Ocean Rim Association (IORA) Conference on Water Security and Sustainability by Government of India and Confederation of Indian Industry, New Delhi, September 06, 2017.

Organizer. 3rd Innovation Water Summit and National Awards for Excellence in Water Management by Confederation of Indian Industry, New Delhi, September 4-5, 2017.

Organizer. International Conference on Water Security and Sustainability in the Blue World, IETF-Water India by Confederation of Indian Industry, New Delhi, February 3, 2017.

Organizer. 3rd India Water Forum, by The Energy and Resources Institute (TERI), New Delhi, April 20-22, 2016

Attendee. Industry Day by Indian Institute of Technology, New Delhi, September 23, 2017.

Attendee. Training and Facilitation in Hydrogeology to Enhance Civil Societies Capacities in Watershed and Groundwater Management, Pune, June 16-July 1, 2016.

Skills

Hydrological, Statistical, and Crop modelling

R, BASH, Python and Visual Basic Analysis for data management

IT Proficient: Microsoft Office

GIS software: ArcGIS, ERDAS Imagine and QGIS

STAN software (short for subSTance flow ANalysis) for Material Flow Analysis

SimaPro software for Life Cycle Assessment

Language Proficiency: English: Proficient, Hindi: Native Language

Extra-curricular

Secretary and former Vice-President of Merced Indian Graduate Student Association, a cultural club, at UC Merced.

Volunteered for engineering day at the Mother and Daughter Science Camp organized by the American Association of University Women (AAUW) in Merced.

CHAPTER 1: INTRODUCTION

1.1. Background

California, the Mediterranean food bowl of the world, sites one of the most agriculturally productive regions in the globe, the San Joaquin Valley (SJV). The SJV produces over half of the California's agricultural outputs and the majority of specialty crops, including fruits, vegetables, nuts, flowers, and nursery crops. However, this multi-billion-dollar agricultural industry relies heavily on irrigation which is facilitated by the hydro-climatological processes, subjected to spatiotemporal variability. In the past decade, this sector has faced water availability challenges due to droughts, regulatory changes, and land conversions (Bedsworth *et al*., 2018). While in the future, forthcoming effects of climate change is expected to aggravate the issue of water availability, though the diversity in crops grown implies a breadth of vulnerabilities to climate changes, but also presents opportunities to mitigate them. Thus, conceiving effective strategy requires exploring the intensifying effects of climate change on agriculture water use, water availability and its conservation, which forms the basis of this research dissertation.

The Mediterranean climate of SJV, which is known for its cool, wet winter and hot, dry summer is susceptible to alterations in water demand due to climate change. The long hot and dry summers already have high level of atmospheric evaporative demand, which is expected to further increase under warming and vapor pressure deficit conditions because of climate change (Sadok *et al*., 2021). Consequently, consumptive water use by the agriculture sector will change in response to increased water demand caused by increasing crop transpiration rates (Kirschbaum and McMillan, 2018; Sadok *et al*., 2020). Conversely, elevated atmospheric carbon dioxide (CO_2) levels, which enhances the water use efficiency in C3 plants, can potentially mitigate the negative effects of warming (Akita and Moss, 1973; Baldocchi and Wong, 2006). The stomatal pores of plant's leaf open during daytime to enable CO_2 diffusion into leaf for photosynthesis (biomass accumulation), leading to water loss from the cells (transpiration). As a result, the higher concentration of available CO_2 reduces the photosynthetic rate and consequently, the transpiration rate. This is a crop-specific phenomenon influenced by their underlying physiological characteristics and optimal temperature tolerance range. Hence, deviations in surrounding temperature and CO_2 levels can affect the usual growth and development patterns of plants. These crops' responses will affect the water fluxes, which will in turn lead to change in the water balance, energy balance and productivity of the region (Xue *et al*., 2021). Altogether, rising evaporative demand and crop phenological perturbations will also affect the ratio of water fluxes including transpiration, evaporation, percolation, and runoff. This influences agricultural water availability and productivity at the watershed scale (Stoy *et al*., 2019) by altering the soil water balance, aquifer recharge, and irrigation practices (Malek et. al, 2017). Thus, climate change impacts and regional-scale demand management should be considered together while simulating future water demands in agriculture dominated basins (Malek et. al, 2017, Hall *et al*., 2023), which is the case of the SJV. However, the contrasting effects of biophysical changes on transpirations rates and diverse cropping patterns indeed makes it challenging to predict the direction of change in water use by the agriculture sector. Nonetheless, agriculture being the largest water user providing vital socioeconomic benefits in SJV requires greater attention.

Since SJV agriculture is dependent on irrigation, timely water availability in this region is essential for unimpeded growth and productivity. The natural surface water supply from precipitation and snowpacks of Sierra Nevada dictates the water availability in this region. Numerous studies in California have shown the climate change will impact precipitation pattern and snowpack storage (Dettinger *et al*., 2011; Pierce *et al*., 2013; Berg and Hall, 2015; Swain *et al*., 2018; Persad *et al*., 2020, Mote *et al*., 2005; Huang *et al*., 2018, Sun *et al*., 2019, Stewart *et al*., 2005). Thus, in the long-term reducing the reliability of agriculture on surface water supply is pertinent. To improve the understanding of changing climate impacts on water availability in space and time, the study of demand and supply at hydrological basin scale is essential (Siad *et al*., 2019, Hall *et al*., 2023).

The restricted water supply during frequent and prolonged droughts in California (Lund *et al*., 2018) along with untenable use of groundwater and accompanied by scanty recharge has resulted critical level of groundwater aquifers (Faunt, 2009; DWR, 2021). To bring groundwater basins to balance, regulations under Sustainable Groundwater Management Act (SGMA) require local groundwater sustainability agencies (GSAs) to assess and manage their groundwater resource in a sustainable manner. The goal of SGMA is to launch and adopt groundwater sustainability plans (GSPs) for critically, highly, and medium over-drafted basins to attain sustainability in the next 20 years. There is a range of options available to reduce the dependence of agriculture on groundwater; by either increasing the supply (groundwater recharge, use recycled water, improving conveyance system, etc.) or by reducing the demand (less water intensive farming, idling land, water trading, etc.) (Hanak *et al*., 2017; Martin *et al*., 2020). For reducing agricultural water use, enhancing supplies could be more constrictive and expensive as compared to the flexible demand-side management strategies (EDF, 2021). Land fallowing is one of the proposed strategies to reduce groundwater overdraft and reduce agriculture water demand. Land fallowing, however, has associated negative externalities and revenue (Howitt *et al*., 2015; Medellin-Azaura, 2019, Sunding and Roland-Holst, 2020; Ayers *et al*, 2022). On the contrary, strategic land repurposing of fallowed land can safeguard equitable benefit distribution for ecosystem and community as a whole by restoring wildlife habitat, soil health, groundwater recharge, renewable energy development, outdoor recreation, or other multi-benefit objectives (Butterfield, 2017; EDF, 2021). Taking land out of production is a major decision, which should be informed by its effectiveness in long-term water savings, alternate opportunities, and challenges.

Many studies have analyzed the impact of climate change on agriculture yield using crop modeling (Lobell and Field, 2011; Malek *et al*., 2017; Rajagopalan *et al*., 2018, Scarpare *et al*., 2022) and Free-air Carbon Dioxide Enrichment (FACE) experimental setup (Akita and Moss, 1973; Ainsworth and Long, 2005; Rogers, *et al*., 2006; O'Leary *et al*., 2015). Crop model estimates crop yields and water use by simulating crop and soil processes as a function of plants physiology, climate, soil science and applied management practices (Stockle, Martin, and Campbell, 1994; Boote *et al*., 2013; Siad *et al*., 2019). O'Leary *et al*. (2015) reviewed widely used crop simulation models for studying various future climate scenarios. They emphasized that these models are robust tools to anticipate crops' response under changing climate against field experimentations. Globally, more than 80% of the climate change impact studies on crops are focused on annual crops such as wheat, maize, rice, soybean, and potato by prevalent models, such as CERES, EPIC, APSIM, CropSyst and DSSAT-CSM+CropGro (Tansey, 2018). Crop growth models can further be enriched for improved estimation of water distribution and ET rates, which

are better represented in hydrological models (Boote *et al*., 2013). Water demand estimation using hydrological models is also prevalent. However, in these models, canopy and rooting characteristics are defined as constant parameters, which does not account for the dynamic biomass accumulation and water use by crops during growing season in agriculture dominated regions (Malek *et al*., 2018). Thus, coupling of both models is expected to yield better results. Siad *et al*. (2019) reviewed 30 coupled hydrologic and crop models' studies having prime objectives of improving ET, CO_2, and nutrient flux estimations using dynamic vegetation module. These coupled models showed that regional hydrological processes are sensitive to crop growth cycle. Thus, a greater emphasis should be given to comprehensive studies which delineate the issue at crop or field level, then scale them to regional scale for effective water resource planning, allocation, and conservation.

1.2. Research gap and questions

The diverse agricultural system of SJV for their types, growth cycle, physiology, and phenology have different water consumptions among them. Two of such higher water usage and profitable crops are almond and pistachio. While studying climate change and atmospheric CO_2 impacts on agriculture, much attention has been given to annual crops and there is limited research on water use on perennial crops. Unlike annual crops, perennial crops, due to their complex phenology, physical stature and high cost of infrastructure are difficult to be taken up for field experiments aimed at exploring climate warming and elevated atmospheric CO_2 impacts. It is hypothesized that the effect of CO_2 enrichment alone may not be enough to offset the climate warming driven increase in water use change in perennial tree crops. To test this hypothesis and address the research the gap, the research question framed in the second chapter of this dissertation is: How perennial tree crop's water use is going to alter under climate change and elevated atmospheric CO_2 (eCO_2) conditions? This is studied by providing a detailed analysis of the crop phenological and evapotranspiration (ETc) changes under climate change and elevated atmospheric CO_2 (eCO_2) conditions using a range of climate scenarios. The existing crop models, when calibrated and validated to local conditions can be useful for the estimation of growth cycles, daily and cumulative seasonal ETc. The study will be beneficial for landowners and farmers to plan ahead for adaptive irrigation practices and select resilient crop varieties.

Addressing the diversity in agricultural water demand is important to understand the water availability challenges. A holistic understanding of the interactions between climate variables, water supply, and crop water use is needed. Studies in the past have lacked detailed analysis on seasonal variations in water demand and supply. They have mostly focused on annual water balance and general water scarcity issues. The hypothesis is that climate change will reduce the surface water reliability for agriculture use. This dissertation addresses the research gap and test the hypothesis in the third chapter by examining how climate change will concurrently alter the timing and magnitude of agriculture water requirements and supply of SJV. The objective is to analyze the water demand by seven major crop types that account for over 65% of the SJV's agricultural land, while estimating the change in water supply reliability. This integrated approach will improve the understanding of crop vulnerabilities to future water shortages, aid for developing effective adaptation and mitigation strategies by the stakeholders, refining hydrological studies and improve climate impact assessments on agriculture.

With reduced surface water availability, the dependence of agriculture on groundwater will further increase. To reduce groundwater overdraft and achieve groundwater sustainability under SGMA, a long-term water conservation strategy is required by reducing land use under agriculture. The water savings suggested by the recent studies under land fallowing/repurposing are short-term and do not account for long-term impacts of climate change. Additionally, there is limited research on the combined effects of multibenefit land repurposing on water savings. It is hypothesized that the tradeoff depends on the current and alternate use of cropland. The research question posed is in the fourth chapter is: How effective are land retirement strategies in water conservation under climate change? This research evaluates the potential of water conservation strategies in the SJV by converting agricultural land to alternative uses, such as habitat restoration, groundwater recharge, and solar energy development. The goal is to provide insights into water saving practices under the constantly changing climate scenarios and suggest which crops have higher potential to save water. Multiple spheres of society will benefit from this study including habitat conservationists, energy sector, landowner, policy and incentive program regulators and community at large.

This dissertation integrates three distinct but related studies to address the complex water management challenges faced by agriculture in California's SJV under changing climate conditions. The second and third chapters of this dissertation focuses on understanding the changing water dynamics under evolving climate scenarios, while examining the water demand and supply. While fourth chapter focuses on the water conservation strategy under climate change. Overall, these studies will enhance knowledge about climate change impact on water use by intensive and irrigated agriculture region in a vulnerable Mediterranean climate system.

1.3. Scientific contribution

This dissertation presents a comprehensive examination of agriculture water availability and conservation in the SJV. Each study contributes unique insights to the challenges and adaptation to climate change. Using data on crops characteristics and field-based observations, climate and environmental impacts on complex perennial tree crops can be used to understand the phenological and water use change at daily to annual time-step. The first chapter on two Mediterranean climate grown crops, almond and pistachio, having similar growth pattern can have distinct vulnerabilities to warming climate due to difference in dormancy requirements and timing of seasonal growth. The impact of elevated CO_2 on water use efficiency can also vary depending on the crop type and characteristics, which will affect the future water needs. The second chapter provides a detailed analysis of how different crop types will respond to climate change highlighting their vulnerabilities to future water shortages due to their difference growth and water requirement patterns. Thus, generalizing results for similar crop types should be avoided and specific crops should be studied individually. Third chapter's novelty lies in performing spatial assessment of potential water-saving strategies refined by water use change for specific crop types under various climate change and land use change scenarios. The study provides quantification of practical solutions for reducing agricultural water demand while considering the socio-economic impacts on the society.

1.4. References

1. Akita, S. and Moss, D.N. (1973) 'Photosynthetic Responses to CO_2 and Light by Maize and Wheat Leaves Adjusted for Constant Stomatal Apertures [1]', *Crop Science*, 13(2), pp. 234–237. Available at: https://doi.org/10.2135/cropsci1973.0011183X001300020025x.
2. Ainsworth, E.A. and Long, S.P. (2005) 'What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2', *New Phytologist*, 165(2), pp. 351–372. Available at: https://doi.org/10.1111/j.1469-8137.2004.01224.x.
3. Ayres, A., Kwon, J., Collins, J. and Morales, J. (2022) 'Land Transitions and Dust in the San Joaquin Valley'.
4. Baldocchi, D. and Wong, S. (2006) *An Assessment of the Impacts of Future CO_2 and Climate on Californian Agriculture*. RESEARCH CEC-500-2005-187-SF. California Climate Change Center.
5. Bedsworth, L., Cayan, D., Franco, G., Fisher, L., Ziaja, S. (2018). Statewide Summary Report. California's Fourth Climate Change Assessment. California Governor's Office of Planning and Research, Scripps Institution of Oceanography, California Energy Commission, California Public Utilities Commission. Publication number: SUM- CCCA4-2018-013
6. Berg, N. and Hall, A. (2015) 'Increased Interannual Precipitation Extremes over California under Climate Change', Journal of Climate, 28(16), pp. 6324–6334. Available at: https://doi.org/10.1175/JCLI-D-14-00624.1.
7. Boote, K.J. *et al.* (2013) 'Putting mechanisms into crop production models', *Plant, Cell & Environment*, 36(9), pp. 1658–1672. Available at: https://doi.org/10.1111/pce.12119.
8. Butterfield Scott, H *et al.* "Identification of Potentially Suitable Habitat for Strategic Land Retirement and Restoration in the San Joaquin Desert." (2017): 1–25. Web. <https://www.scienceforconservation.org/assets/downloads/SLR-Habitat_-2017-lo.pdf>.
9. Dettinger, M. D. *et al.* Atmospheric rivers, floods and the water resources of California. Water, 3(2), 445–478. (2011). https://doi.org/10.3390/w3020445
10. Environmental Defense Fund (EDF). *Advancing Strategic Land Repurposing and Groundwater Sustainability in California*. N.p., (2021). Web.
11. Faunt, C.C., ed., (2009), Groundwater Availability of the Central Valley Aquifer, California: U.S. Geological Survey Professional Paper 1766, 225 p.
12. Hall, S.A., Adam, J.C., Yourek, M.A., Whittemore, A.M., Yorgey, G.G., Scarpare, F., Liu, M., McLarty, S., Asante-Sasu, C., McClure, S., Turk, J., Haller, D., Padowski, J., Deshar, R., Brady, M.P., Rajagopalan, K., Barber, M.E., Weber, R., Stockle, C.O., Goodspeed, H.L., Gustine, R.N., Kondal, A., Yoder, J., Deaver, B., Downes, M., Tarbutton, S., Callahan, M., Price, P. Roberts, T., Stephens, J., Valdez, W. (2022) Columbia River Basin Long-Term Water Supply and Demand Forecast. 2021 Washington State Legislative Report. Publication No. 21-12-006. Washington Department of Ecology, Olympia, WA. 284 pp.
13. Hanak, Ellen *et al.* (2017) Water Stress and a Changing San Joaquin Valley. *Public Policy Institute of California*.

14. Howitt, R. and Sunding, D. (2003). Water infrastructure and water allocation in California. *California Agriculture: Dimensions and Issues*, pp.181-190.
15. Huang, X., Hall, A.D., Berg, N., (2018). Anthropogenic Warming Impacts on Today's Sierra Nevada Snowpack and Flood Risk. Geophysical Research Letters 45, 6215–6222. https://doi.org/10.1029/2018GL077432
16. Kirschbaum, M.U.F. and McMillan, A.M.S. (2018) 'Warming and Elevated CO2 Have Opposing Influences on Transpiration. Which is more Important?', *Current Forestry Reports*, 4(2), pp. 51–71. Available at: https://doi.org/10.1007/s40725-018-0073-8.
17. Lobell, D.B. and Field, C.B. (2011) 'California perennial crops in a changing climate', *Climatic Change*, 109(S1), pp. 317–333. Available at: https://doi.org/10.1007/s10584-011-0303-6.
18. Lund, J., Medellin-Azuara, J., Durand, J. and Stone, K. (2018) 'Lessons from California's 2012–2016 Drought', Journal of Water Resources Planning and Management, 144(10), p. 04018067. Available at: https://doi.org/10.1061/(ASCE)WR.1943-5452.0000984.
19. Malek, K. *et al*. (2017) 'VIC–CropSyst-v2: A regional-scale modeling platform to simulate the nexus of climate, hydrology, cropping systems, and human decisions', Geoscientific Model Development, 10(8), pp. 3059–3084. Available at: https://doi.org/10.5194/gmd-10-3059-2017.
20. Martin, P.L., Goodhue, R.E., Wright, B. and Giannini Foundation of Agricultural Economics (eds) (2020) California agriculture: dimensions and issues. Berkeley, California: University of California, Giannini Foundation of Agricultural Economics, Division of Agriculture and Natural Resources (Giannini Foundation information series, 20–01). Available at: https://s.giannini.ucop.edu/uploads/pub/2021/01/26/chapter_1_introduction_2020.pdf.
21. Medellín-Azuara, J. *et al*. "Technical Appendix C: Potential Economic Impacts of Reducing Water Use on San Joaquin Valley Agriculture. Water and the Future of the San Joaquin Valley." *Public Policy Institute of California* February (2019): n. pag. Web.
22. Mote, P.W., Hamlet, A.F., Clark, M.P. and Lettenmaier, D.P. (2005) 'DECLINING MOUNTAIN SNOWPACK IN WESTERN NORTH AMERICA', Bulletin of the American Meteorological Society, 86(1), pp. 39–50. Available at: https://doi.org/10.1175/BAMS-86-1-39.
23. O'Leary, G.J. *et al.* (2015) 'Response of wheat growth, grain yield and water use to elevated CO 2 under a Free-Air CO 2 Enrichment (FACE) experiment and modelling in a semi-arid environment', *Global Change Biology*, 21(7), pp. 2670–2686. Available at: https://doi.org/10.1111/gcb.12830.
24. Persad, G.G., Swain, D.L., Kouba, C., Ortiz-Partida, J.P., 2020. Inter-model agreement on projected shifts in California hydroclimate characteristics critical to water management. Climatic Change 162, 1493–1513. https://doi.org/10.1007/s10584-020-02882-4
25. Pierce, D.W., Das, T., Cayan, D.R., Maurer, E.P., Miller, N.L., Bao, Y., Kanamitsu, M., Yoshimura, K., Snyder, M.A., Sloan, L.C., Franco, G. and Tyree, M. (2013) 'Probabilistic estimates of future changes in California temperature and precipitation using statistical and dynamical downscaling', Climate Dynamics, 40(3–4), pp. 839–856. Available at: https://doi.org/10.1007/s00382-012-1337-9.

26. Rajagopalan, K. *et al*. "Impacts of Near-Term Climate Change on Irrigation Demands and Crop Yields in the Columbia River Basin." *Water Resources Research* 54.3 (2018): 2152–2182. Web.
27. Rogers, A., Ainsworth, E.A. and Kammann, C. (2006) 'FACE Value: Perspectives on the Future of Free-Air CO2 Enrichment Studies', in J. Nösberger *et al*. (eds) *Managed Ecosystems and CO2*. Berlin/Heidelberg: Springer-Verlag (Ecological Studies), pp. 431–449. Available at: https://doi.org/10.1007/3-540-31237-4_24.
28. Sadok, W., Lopez, J.R. and Smith, K.P. (2021) 'Transpiration increases under high-temperature stress: Potential mechanisms, trade-offs and prospects for crop resilience in a warming world', Plant, Cell & Environment, 44(7), pp. 2102–2116. Available at: https://doi.org/10.1111/pce.13970
29. Scarpare, F.V.; Rajagopalan, K.; Liu, M.; Nelson, R.L.; Stockle, C.O. (2022) Evapotranspiration of Irrigated Crops under Warming and Elevated Atmospheric CO_2: What Is the Direction of Change? *Atmosphere*, 13, 163. https://doi.org/ 10.3390/atmos13020163
30. Siad, S.M. *et al.* (2019) 'A review of coupled hydrologic and crop growth models', *Agricultural Water Management*, 224, p. 105746. Available at: https://doi.org/10.1016/j.agwat.2019.105746.
31. Stewart, I.T., Cayan, D.R., Dettinger, M.D., (2005). Changes toward Earlier Streamflow Timing across Western North America. Journal of Climate 18, 1136–1155. https://doi.org/10.1175/JCLI3321.1
32. Stockle, C.O., Martin, S.A. and Campbell, G.S. (1994) 'CropSyst, a cropping systems simulation model: Water/nitrogen budgets and crop yield', Agricultural Systems, 46(3), pp. 335–359. Available at: https://doi.org/10.1016/0308-521X(94)90006-2.
33. Stoy, P.C. *et al*. (2019) 'Reviews and syntheses: Turning the challenges of partitioning ecosystem evaporation and transpiration into opportunities', Biogeosciences, 16(19), pp. 3747–3775. Available at: https://doi.org/10.5194/bg-16-3747-2019.
34. Sun, F., Berg, N., Hall, A., Schwartz, M. and Walton, D. (2019) 'Understanding End-of-Century Snowpack Changes Over California's Sierra Nevada', Geophysical Research Letters, 46(2), pp. 933–943. Available at: https://doi.org/10.1029/2018GL080362.
35. Sunding, David, and David Roland-Holst. "Blueprint Economic Impact Analysis: Phase One Results." (2020): n. pag. Web.
36. Swain, D.L., Langenbrunner, B., Neelin, J.D. and Hall, A. (2018) 'Increasing precipitation volatility in twenty-first-century California', Nature Climate Change, 8(5), pp. 427–433. Available at: https://doi.org/10.1038/s41558-018-0140-y.
37. Tansey, M. (2018) Plant Physiological Responses to Atmospheric Forcings Affecting Crop Water Use and Yields: Literature Review and Model Comparisons. RESEARCH ST-2018-1858-01. Sacramento: Department of the Interior, Bureau of Reclamation, Mid Pacific Region, p. 183. Available at: https://www.usbr.gov/research/.
38. Xue, J., Huo, Z., Kisekka, I., (2021). Assessing impacts of climate variability and changing cropping patterns on regional evapotranspiration, yield and water productivity in California's San Joaquin watershed. Agricultural Water Management 250, 106852. https://doi.org/10.1016/j.agwat.2021.106852/.

CHAPTER 2: WATER USE DYNAMICS OF ALMOND AND PISTACHIO CROPS IN THE MEDITERRANEAN REGION AMID CLIMATE CHANGE

2.1. Abstract

Almond and pistachio tree crops are socio-economically significant crops grown in California's San Joaquin Valley (SJV). Continuing commercial production with efficient irrigation planning under changing climate requires an extensive understanding of their biophysical interactions such as altered phenology, biomass accumulation, transpiration, and other processes. This study aims to investigate the impact of climate change (warming-only) and elevated atmospheric CO_2 (eCO_2) levels on phenology and water use (ETc) responses by almonds and pistachios using VIC-CropSyst, a coupled process-based crop-hydrology model. The model was calibrated and validated using observations on crop evapotranspiration. The simulated crop responses to warming-only and eCO_2 revealed compounding effects on chill accumulation, phenology, biomass accumulation, and eventually on crop water use. The active growth period from bud break to dormancy was prolonged by 10-25 days for both crops under simulated Representative Concentration Pathways (RCP4.5 and RCP8.5) scenarios compared to the baseline. The annual ETc under warming-only scenarios showed a slight increase for almonds (1% under RCP4.5 and 3% under RCP8.5) and a higher increase for pistachios (8% under both RCP4.5 and RCP8.5) by the mid-21st century. These increases in ETc translate to 260 (almonds) and 180 (pistachios) million m^3/year of additional water for irrigation in the absence of eCO_2 effects. The eCO_2 is expected to moderately reduce irrigation demand by 35 million m^3/year for almonds and increase by 140 million m^3/year for pistachios over the baseline. The outcomes can guide decision-makers to anticipate potential threats and concoct adaptive strategies by managing irrigation and choosing suitable cultivars or alternate crops.

2.2. Introduction

The well-suited Mediterranean climate and irrigation water availability has made California a global leader in agriculture production, especially for high-value specialty crops. California is the leading producer of commercial almonds and pistachios in the United States. Production of these nut crops are ranked second and fifth top crop commodities in the state, respectively (CDFA, 2021). In the San Joaquin Valley (SJV) of California, they hold higher positions in agricultural valuation and together cover ~36% of the total irrigated acreage (USDA, 2020). Market-driven demand has encouraged farmers to cultivate vast irrigated almond and pistachio orchards. In the past few decades, these nuts' quality and yields have improved in SJV with the use of superior yielding varieties, optimized orchard planning (planting and spacing), irrigation management, maximized cross-pollination, agrochemical application, and choosing drought and disease-resistant rootstocks (Micke, 1996; Durán-Zuazo *et al.*, 2020). However, being perennial tree crops, they have inflexible water needs in a hydrologic environment with increasing variability. The advancements may not suffice to tackle the forthcoming difficulties in maintaining potential crop water use efficiency (yield produced per unit of water) due to evolving water policies and uncertainties in water availability enforced by climate change.

Thus, it is necessary to ascertain the impact of climate change on seasonal water use by these important nut crops to minimize future economic losses and sustain productivity.

The crop's growth and water use depend on climate (e.g., air temperature, solar radiation, and relative humidity) and biophysical variables (such as atmospheric CO_2 concentration, nutrients, and crop characteristics) (Goldhamer, 1996; Allen *et al.*, 1998; Scarpare *et al.*, 2022). Global mean temperature is rising due to elevated levels of atmospheric CO_2 (eCO_2) and other greenhouse gases. In California, a temperature increases of up to 2.7 °C by mid-21st century and to 4.4 °C by the end of this century is projected (Bedsworth *et al.*, 2018). Additionally, frequent droughts, extreme hot temperatures, warmer winters, shorter precipitation seasons, and earlier snowmelt are becoming a new normal (Bedsworth *et al.*, 2018). All these changes will have adverse effects on agriculture due to reducing soil moisture storage, increasing potential evapotranspiration, and altering crop phenology as well as physiology, leading to unusual crop growth patterns and declined yields (Malek *et al.*, 2017; Pathak *et al*., 2018). Heat stress is also projected to increase in the future, leading to increased atmospheric vapor pressure deficit, and in response to this, crops will increase transpiration rates to lower canopy temperature (Sadok *et al*., 2021). On the contrary, eCO_2 is known to decrease stomatal conductance, leading to lesser water vapor diffusion from leaves and higher biomass accumulation. It thus aids leaf photosynthetic rate and water use efficiency in C3 species, which may offset the adverse impacts of warming (Akita and Moss, 1973; Baldocchi and Wong, 2006). Even under water-scarce conditions, eCO_2 can ameliorate crop water deficit by reducing transpiration rates; however, it cannot entirely offset the impact of warming temperature (Hatfield and Dold, 2019). Photosynthesis ceases when the optimum temperature is exceeded (Baldocchi and Wong, 2006), and reduced evaporative cooling due to the closure of stomata can permanently damage the crop (Pathak *et al*., 2018). Many studies have analyzed the impact of climate change on agriculture using crop modeling (Stockle *et al*., 2010; Lobell and Field, 2011; Medellin-Azuara, 2011; Malek *et al*., 2018; Rajagopalan *et al*., 2018, Tansey, 2018) and Free-Air Carbon Dioxide Enrichment (FACE) experimental setup (Akita and Moss, 1973; Ainsworth and Long, 2005; Rogers, *et al*., 2006; O'Leary *et al*., 2015). Crop models estimate water use and yield by simulating biological and soil processes as a function of crop physiology, climate, soil's physical and chemical properties, and applied management practices (Stockle, *et al*., 1994; Boote *et al*., 2013; Siad *et al*., 2019). O'Leary *et al.* (2015) reviewed widely used crop simulation models for studying impacts of various future climate scenarios. Their work emphasized that these models are robust tools to anticipate crops' response under changing climates against field experimentations.

Globally, more than 80% of the climate impact studies on crops are focused on annual crops such as wheat, maize, rice, soybean, and potato by prevalent models (Tansey, 2018), while the impact on perennial tree crops is limited and poorly understood (Stockle *et al*., 2011). Several researchers have predicted increasing orchard water requirements in Mediterranean regions under changing climatic conditions for almonds (Funes *et al.*, 2021) and pistachios (Ahmadi and Baaghideh, 2020). However, little is known about the underlying mechanisms. Quantifying the intricate interplay between climate change and irrigation losses necessitates the development of a spatially explicit, large-scale hydrological simulation platform (Malek *et al.*, 2018). This platform should incorporate the dynamic interactions

between the hydrologic cycle, irrigation management strategies, and crop growth processes, encompassing both phenology and management practices.

At an orchard level, crop evapotranspiration (ETc) represents water loss from leaves as transpiration and from soil and canopy as evaporation (Lawrence *et al*., 2007). Transpiration directly connects the eco-hydrological processes by interacting with CO_2 transfer and vegetation growth through stomata. Evaporation, in contrast, links indirectly through alterations in vegetation coverage and shading of the soil surface (Zhang, *et al*., 2017). Climatic and phenological perturbations can affect the ratio of transpiration, evaporation, and other water fluxes (percolation, runoff), which influences agricultural water availability and productivity at the watershed scale (Stoy *et al*., 2019). Partitioning ETc to canopy transpiration (T) and surface evaporation (E) can help understand future crop water use (Kirschbaum and McMillan, 2018) to further improve irrigation efficiency in water-limited systems (Knipper *et al.*, 2023). However, partitioning ETc in an agricultural setting has yet to be given the required attention, among other aspects (Malek *et al*., 2018). Crop models can be powerful tools in providing insights into how stomatal conductance, leaf area, plant development stages and climate influence the T/E ratio.

Another facet of climate change's impact on crops is growth pattern changes. Some studies have used observations and process-based models to study changes in phenological stages in almonds (Gitea *et al.*, 2019; Lorite *et al.*, 2020) and pistachios (Kallsen, 2020; 2017; Ahmadi and Baaghideh, 2020; Ahmadi *et al.*, 2021; Ghrab, *et al.*, 2022). Temperature insufficiency or excess exposure can affect both, active seasonal development (during spring to fall) and dormant resting state (in winter). In the active growth period, either accumulating insufficient heat units or exposure to extreme heat are detrimental. Temperature insufficiency during the dormant season is the lack of chill hours caused by warming winters or frost damage due to extreme cold. Sufficient chilling promotes timely bud break, bloom, cell differentiation, and vegetative growth progression throughout the active season. A study by Baldocchi and Waller (2014) used satellite and weather station data to show that there were 46% fewer foggy days between 1981 and 2014 in Central Valley, California. Foggy conditions promote colder temperatures for achieving a period of soil dormancy, shielding plant buds from the sun, and helping them accumulate winter chill. Declining yields have been reported due to altered phenology and insufficient chill hours for almond (Ghrab *et al.*, 2016; Tombesi *et al.*, 2010; Ghrab *et al.*, 2022) and pistachio (Kallsen, 2017; Zhang and Ranford, 2021).

To the best of our knowledge, there is lack of study in California that has holistically investigated the changes in seasonal phenology and water fluxes by perennial almond and pistachio tree crops under climate change and eCO_2 scenarios. The increase in warming temperature will lead to rise in water requirements by crops. With increasing atmospheric CO_2, however, the water use efficiency of perennial tree crops (having C3 photosynthetic pathway) will increase. The hypothesis is that the effect of CO_2 enrichment alone will not be enough to offset the temperature driven increase in crop water use. This research aims to analyze the changes in seasonal growth patterns and water use under warming and eCO_2 by the two most important nut tree crops in the SJV. To achieve this, we took advantage of a large-scale, state-of-the-art, coupled hydrology-crop model and evaluated its performance in simulating ETc in variable soil and climatic conditions. This study quantified seasonal crop development, average daily use, cumulative water use, and shift in partitioned

transpiration and evaporation losses under baseline, moderate Relative Concentration Pathways (RCP4.5), extreme (RCP8.5) climate change and eCO_2 scenarios.

2.3. Methods

2.3.1. Study area

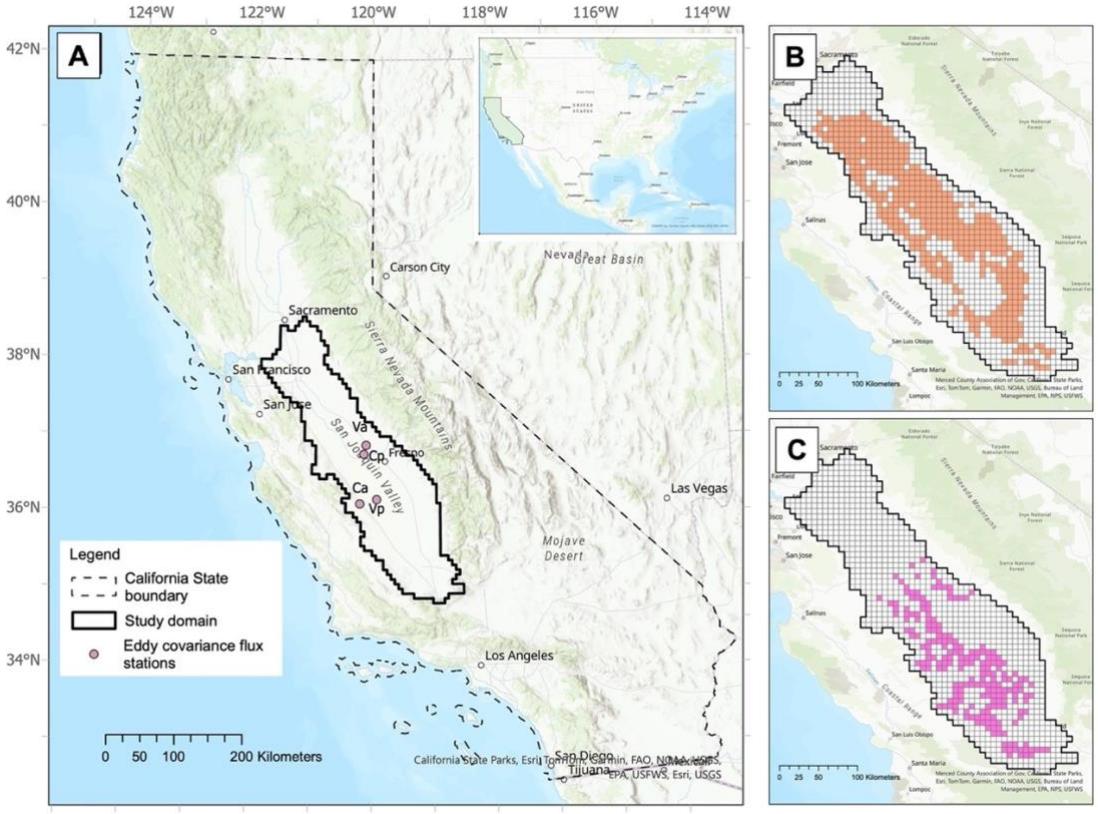


Figure 2.1 Panel A shows study domain of San Joaquin Valley in California. Circles represent calibration (Ca & Cp; where "a" represents almond and "p" represents pistachio) and validation (Va & Vp) sites of eddy covariance flux stations providing daily observed ET values. Panels B and C show the grid locations with ≥10% of the grid area under almond (B) and pistachio (C) crops per USDA, 2020 data.

Situated in the middle of California, SJV consists of vast alluvial plain land bounded by Sierra Nevada mountains on the east and Coastal mountains on the west (Figure 2.1). It encompasses part of 8 counties: San Joaquin, Stanislaus, Merced, Madera, Fresno, Kings, Tulare, and Kern. SJV has a Mediterranean climate with hot, dry summer and cool, wet winter; it receives an annual precipitation of 350 mm, with ~75% occurring between October and March. The dominant soil type is clay loam soil in the western parts and sandy loam in the central and eastern parts of the SJV, with higher salinity in the central part (Walkinshaw *et al.*, 2022). SJV comprises approximately 2.3 million hectares (5.7 million acres) of irrigated agricultural areas. Of those areas, almond and pistachio orchards cover ~26% and ~10%, respectively (USDA, 2020). Both crops are fully irrigated, mainly through micro-irrigation systems. An illustration of the almond crop's annual growth cycle and water use is provided in Appendix A Figure S1.

2.3.2. VIC-CropSyst model

This study uses a gridded, process-based, and coupled hydrology-crop model, VIC–CropSyst v.3, which provides advantages over each stand-alone model (Adam *et al.*, 2015). CropSyst (Stockle *et al.*, 1994), a point-scale crop model is embedded into the Variable Infiltration Capacity model (VIC, Liang *et al.*, 1994; Cherkauer *et al.*, 2003), a gridded large-scale, semi-distributed hydrologic model (Adam *et al.*, 2015). The framework integration of these models is described by Adam *et al.* (2015), Malek *et al.* (2017; 2018), and Rajagopalan *et al.* (2018). VIC-CropSyst simulates water and energy fluxes at daily temporal and 1/16th degree spatial grid scale (~6 x 6 km grids) over a hydrological region accounting for heterogeneous crops/vegetations, soil, climate, crop phenology, and management practices to explore interactions between hydrological fluxes and agricultural processes (Adam *et al.*, 2015). The model uses the small grass Penman-Monteith reference evapotranspiration (ETo) equation based on Allen *et al.* (1998). ETo reflects potential atmospheric water demand under the influence of local climate for grass in full development stage (i.e., leaf area index (LAI) = 3 m^2/m^2) under constant stomatal resistance of 70 s/m (Allen *et al*., 1998). To calculate ETc, crop coefficient that represents the crop development stage is used. Seasonal phenological stages are determined by the accumulated daily heat units (in growing degree days) using a linear thermal response curve model and effective chilling hours are calculated using the Utah Chilling Unit Model (Richardson *et al*., 1974).

The biomass accumulation is limited by transpiration (water-limited) and radiation use efficiency (radiation-limited). The harvest yield is dependent on total biomass accumulated at physical maturity and is computed based on the maximum fruit load and fraction of total solids parameters. The transient CO_2 concentration is specified for each simulation year and its effect on biomass production and potential transpiration is adjusted in the model as per Scarpare *et al*. (2022). The biomass gain ratio of transient CO_2 concentration to the baseline (i.e., pre-industrial CO_2 level of 350 ppm) is fitted with a non-rectangular hyperbola curve by using FACE experiments' results (Equation 1).

$$\frac{Biomass\ at\ eCO_2}{Biomass\ at\ baseline\ CO_2} = \frac{\alpha[CO_2]+\beta-\sqrt{(\alpha[CO_2]+\beta)^2-4\theta\alpha\beta[CO_2]}}{2\theta} \quad \text{....Equation 1}$$

where α is the initial slope of the CO_2 assimilation curve, β is the asymptote (i.e., gain ratio at CO_2 saturation), θ is the co-limitation which defines the convexity of the curve, $[CO_2]$ is atmosphere CO_2 concentration. The eCO_2 effect on potential transpiration (f_T, converting factor from the standard contemporary FAO56 values to transient eCO_2 concentrations) is parameterized with a nonlinear response derived by Allen (1990; Equation 2).

$$f_T = \frac{\Delta+\gamma(r_c+r_a)/r_a}{\Delta+\gamma(r_{co}+r_a)/r_a} \quad \text{.....Equation 2}$$

where Δ is the slope of the saturation vapor pressure function of temperature, γ is the psychrometric constant, r_a is the aerodynamic resistance, r_c is the FAO56 canopy resistance (specified at 359 ppm) adjusted to baseline CO_2, and r_{co} is the FAO56 canopy resistance adjusted to eCO_2. The model has a mechanistic irrigation

module to estimate evaporative losses (soil surface, canopy intercepted water, and irrigation droplets), non-evaporative losses (baseflow and runoff), and irrigation amount and frequency (Malek *et al*., 2017). The irrigation was applied using drip irrigation, assuming 97% efficiency and a maximum capacity of 30 mm/day. Considering the fixed nature of the drip efficiency, evaporative losses via droplets were not included in the total ETc. The application was scheduled whenever soil moisture maximum allowable depletion of 10% of available water for crop uptake was observed at 0.7 fraction of total root depth (1.2 m).

2.3.3. Input data

VIC-CropSyst uses climate, land cover, atmospheric CO_2, soil, crop/vegetation phenology, physiology, and management information as input data (more details in Table S1). For calibration and validation purposes, the model was forced with gridded climate data for 1980-2020 (adapted from Abatzoglou, 2013). For future climate change projections, Multivariate Adaptive Constructed Analogs downscaled (MACA, Abatzoglou and Brown, 2012) climate data from four Global Circulation Models (GCMs) from the Coupled Model Intercomparison Project 5 (CMIP5) were chosen. These four GCMs are HadGEM2-ES365 (warm/dry), CNRM-CM5 (cool/wet), CanESM2 (average), and MIROC5 (variability across all 10 GCMs). Climate change projections under two RCPs from these four GCMs represent a range of possible scenarios and are among the recommended 10 CMIP5 models in California's Fourth Climate Change Assessment for hydrological studies (Bedsworth *et al.*, 2018). The transient CO_2 concentrations were used for RCP4.5 and RCP8.5 scenarios (IPCC, 2014; Meinshausen *et al.*, 2011)

Soil input data adapted at the model's resolution for textural characteristics, distribution, and hydrology were developed using STATSGO2 data. The calibrated soil parameters were taken from Maurer *et al.* (2002). We updated this data using the latest climate averages and changed soil layers (from 3 to 17 layers). Land cover data for the SJV boundary was sourced from the USDA-NASS Crop Data Layer (USDA, 2020), available at 30 m spatial resolution. Then, fractional land cover for natural vegetation and crop classes was calculated at each grid to select grids with 10% of the area covered by almond and pistachio crops (Figure 2.1, panels B and C). Daily LAI for these two nut crops were calculated by the CropSyst model. Monthly LAI for other vegetation were input as fixed values in VIC vegetation file (sourced from Bohn and Vivoni, 2019).

The CropSyst model simulates the crop-specific parameters such as growing cycle length, canopy evolution, initial root zone soil moisture, root depth and distribution, and biomass accumulation. The model was parametrized for the fruit bearing age of these tree crops (i.e., ~3-4 years for almonds and ~5-7 years for pistachios). The average start dates of bud break, flowering, nut-filling, maturity, and dormancy stages were input as growing degree day values. Parameters related to phenology, ETc and crop yield were taken from California-specific studies and literature (DeJong, 1996; Goldhamer, 1996; Kester *et al*., 1996; Micke, 1996; Lampinen *et al.*, 2006; Sanden 2010; Ferguson, 2014; Doll and Shackel, 2015; Goldhamer and Beede, 2016; Ferguson and Kallsen, 2016; Doll, 2017; Kallsen 2017; Kallsen *et al.*, 2017; *Gordon et al*., 2020). Observed yield data (nut kernels weight per unit area) for the most dominant cultivars growing in SJV were used to parameterize the model (*viz.* Nonpareil almond and Kerman pistachio) (Lampinen *et al.*, 2006; Lampinen *et al.*, 2016; Doll, 2017; Kallsen *et al.*, 2017; *Gordon et al*., 2020). These sources were chosen from the studies meeting full crop water requirements, which

provided the baseline for potential growth and yield. The potential yield chosen for almonds was 2,565 kg/ha and for pistachios was 3,860 kg/ha, which were close to average of observed yields. The model does not account for pruning or weight training management. The crop parameter related root depth, maximum canopy cover, height, and tree spacing were obtained from the literature.

2.3.4. Model calibration and validation

Crop water use and yields are sensitive to crop development stages and are influenced by the climatic conditions in which they are grown. Sensitive crop parameters are identified based on sensitivity analysis by Rajagopalan *et al*. (2018) and Adam *et al*. (2022). Malek *et al*. (2017) found negligible sensitivity for soil moisture content, crop growth, and irrigation fluxes against soil calibration parameter ranges. To improve ETc simulation, we further extended the sensitivity analysis to include leaf water potential and daily maximum water uptake. The model was calibrated using sensitive parameters for local climate and management practices (Table S1). All simulations were performed under fully irrigated and non-stressed conditions, such that crop growth was governed by solar radiation, air temperature, CO_2 atmospheric concentration, and crop characteristics. Calibration for the large SJV region over 30 years (1981-2020) was performed using 12 random sample grid cells with variable climate and soil depth from each county. Because of limited availability of actual initial soil profile conditions (available water), the first 4-5 years of the simulated period were considered as 'spin-up' after which conditions are assumed to have achieved a realistic equilibrated state. For this reason, the simulated results for these years were omitted from analysis.

First, the days to reach phenological development stages (bud break, bloom, peak LAI, filling, maturity, and dormancy) and total seasonal growth length of crops were calibrated by adjusting the heat accumulation growing degree-day values based on observed dates (Micke, 1996; Lampinen *et al.*, 2006: Ferguson and Kallsen, 2016). Then, seasonal maximum LAI and water stress index were calibrated by changing maximum root depth, canopy cover fraction, light extinction coefficient, transpiration use efficiency, and leaf water potential. Canopy growth drives water uptake, which is critical to supplying nutrients and water for potential crop yield. Subsequently, to produce reasonable ETc, maximum water uptake, crop coefficient, and leaf water potential were adjusted to match observations from field studies (Sanden, 2014; Doll, 2017; Anderson, 2020a, 2020b, 2020c, 2020d, 2020e; Helalia, *et al.*, 2021). The postharvest trees' daily ETc values were adjusted for leaf loss from mechanical harvest, less frequent irrigation, shorter day length, and lower temperature by lowering the kc value to ~70% of peak value. The product of daily kc and ETo gives ETc, i.e., $ETc = kc \times ETo$. Lastly, the dry matter yield was calibrated to match the potential yield by fine-tuning transpiration-use efficiency, maximum load, moisture content, and optimal temperature for net photosynthesis. Nut development and growth fraction were adjusted to relate with the pattern described by Kester *et al*. (1996).

Daily observed ETc values from eddy covariance flux towers that measures the water flux from soil and crop canopy to the atmosphere were sourced from the Ameriflux network (Anderson, 2020a, 2020b, 2020c, 2020d, 2020e; Helalia, *et al.*, 2021). We used data from four flux towers in SJV to calibrate (Ca & Cp) and validate (Va & Vp) daily ETc during years 2017, 2018, and 2019 (two towers in almond: Ca and Va and two in pistachio orchards: Cp and Vp). The model was evaluated using commonly used error indices and goodness of fit models, namely, root mean square error (RMSE), percent bias (PBIAS), coefficient of variation (R^2), and Klingon-Gupta

efficiency (KGE). Additionally, the cumulative yearly ETc for both crops were also compared. Modeled daily ETc output was also compared with the widely used California Irrigation Management Information System (CIMIS) gridded product, Spatial CIMIS (DWR, 2022). It combines remotely sensed satellite data with traditional CIMIS station data to produce maps of daily ETo on a 2-km grid. After upscaling the data to match VIC-CropSyst resolution, ETc for each nut crop and grid is calculated by multiplying ETo with weekly kc (Allen *et al*. 1998, Sanden, 2010).

2.3.5. Scenario analysis

The calibrated model was forced with climate change and eCO_2 scenarios to project their individual and combining impacts on almonds and pistachios' consumptive water use. The simulation experiments consisted of four GCMs, three RCP scenarios, i.e., no climate change (baseline, 1975-2005), moderate change (RCP4.5, 2006-2099), and extreme change (RCP8.5, 2006-2099), along with two atmospheric CO_2 concentrations scenarios: 'warming-only' (i.e., fixed CO_2 at 360 ppm) and 'warming + eCO_2' (transient CO_2 330-927 ppm between 1975-2099). Overall, 24 simulation scenarios (4 GCMs x 3 RCPs x 2 CO_2) were developed sharing same soil, land use, and irrigation management. Model ensemble results are aggregated by averaging VIC-CropSyst outputs from four individual GCM runs, for baseline, each RCP and eCO_2 scenarios. After excluding spin-up simulations, 2010-2099 period was broken up at decadal timeframe and compared with baseline period (1980-2005). First, chill accumulation period was analyzed to anticipate the change in dormancy length. In case sufficient chill hours were not available to fulfil dormancy-breaking requirements, the crops in the model were forced to bud break on DOY (Day of the Year) 90 (assuming dormancy-breaking management strategies were implemented). Thereafter, the start day and length of the active period's phenological stages were evaluated at grid and decadal time scales. The period of crop growth considered here include the days when leaf area index was greater than zero, but exclude budbreak, flowering, senescence, and dormancy period for perennial crops. Then, average daily ETc representing crop water use in the active crop growing period were compared with the baseline averages for the period of active growth when leaf area index is greater than zero. ETc's partitioned components, actual transpiration (T) and evaporation (E) were analyzed, to determine if the change in ETc is driven mainly by change in crop process changes or surrounding evaporation. Finally, results for annual cumulative ETc during maturity, postharvest (maturity to start of dormancy), and active growth periods were analyzed for climate change and CO_2 impacts.

2.4. Results

2.4.1. Model evaluations

The model captured almond and pistachio crops' phenological progression well concerning growing conditions such as chill requirements, heat units, and evapotranspiration. Simulated days to reach phenological stages were close to observed dates for both crops (Table 2.1-a). In addition, the model's performance in capturing ETc was satisfactory with KGE and R^2 values close to 0.8 for both crops (Table 2.1-b & Figure 2.2-A). PBIAS was higher than 10%, possibly because the model underestimated daily ETc values during the spring season's initial canopy phases. The reason can also be related to the differences between simulated starting dates of irrigation in the model and actual orchard sites. The automatic irrigation in the model is based on soil moisture depletion rates, while actual irrigation may depend on farmer's decision, availability of water and other resources. This

underestimation can also be attributed to possible understory vegetation in the orchards, i.e., cover crops and other secondary vegetation, which were not accounted for in the simulation. The simulated annual cumulative ETc had similar yearly trends as observed data from calibration and validation sites. More details are provided in Appendix A (Figure S2 A-F).

Table 2. 1:Model calibration and evaluation results. a. Observed and modeled median developmental phenological stages' dates (DOY in parentheses) for almond and pistachio crops. b. Model performance using the goodness of fit models against observed daily ETc over calibration and validation sites of eddy covariance flux-tower. Validation results against daily ETc Spatial CIMIS (CIMIS) estimations over all grids of respective crops.

a. The median of observed and modeled dates of phenological stages				
Stages	Almond		Pistachio	
	Observed	Modeled	Observed	Modeled
Flowering	20-Feb (50)	21-Feb (51)	10-Apr (100)	10-Apr (103)
Maximum LAI	10-Apr (100)	11-Apr (101)	15-Jun (160)	15-Jun (160)
Fruit filling	15-Mar (80)	17-Mar (82)	10-Jun (120)	10-Jun (120)
Nut maturity	1-Sep (244)	1-Sep (244)	24-Sep (266)	24-Sep (265)
Tree dormancy	15-Nov (320)	15-Nov (319)	15-Nov (320)	15-Nov (319)

b. Model performance on daily ETc over calibration (Ca & Cp), validation (Va & Vp) sites and over all grids against Spatial CIMIS						
Goodness of fit models	Calibration Flux-tower	Validation		Calibration Flux-tower	Validation	
		Flux-tower	CIMIS		Flux-tower	CIMIS
KGE	0.8	0.83	0.87	0.8	0.79	0.8
R^2	0.85	0.81	0.88	0.82	0.82	0.8
RMSE (mm/day)	1.3	1.39	0.95	1.39	1.41	1.3
PBIAS (%)	-14	-13	2.5	-17	-18	-6.7

The model simulated ETc was in close agreement with the annual average daily ETc obtained from spatial CIMIS for the period 2011-2020 (Figure 2.2-B). The model showed higher spatial variability in ETc than spatial CIMIS, which can be attributed to distinct data aggregation and scaling methods. The individual year's R^2 values for almonds varied between 0.82-0.90, and pistachios varied between 0.74-0.88. Most RMSE values for almonds were between 0.8 to 1.1 mm/day, and for pistachios, were between 1 to 1.6 mm/day. Generally, the model slightly overestimated the average daily ETc values for almonds and underestimated that for the pistachios for almost all years. Daily values were biased between -5 to 10% for almonds and 0 to -15% for pistachios (more information in Appendix A Figure S2 G-H). The differences in values can be owed to the kc values simulated differently in the model than reported values used to calculate ETc from CIMIS reference ET.

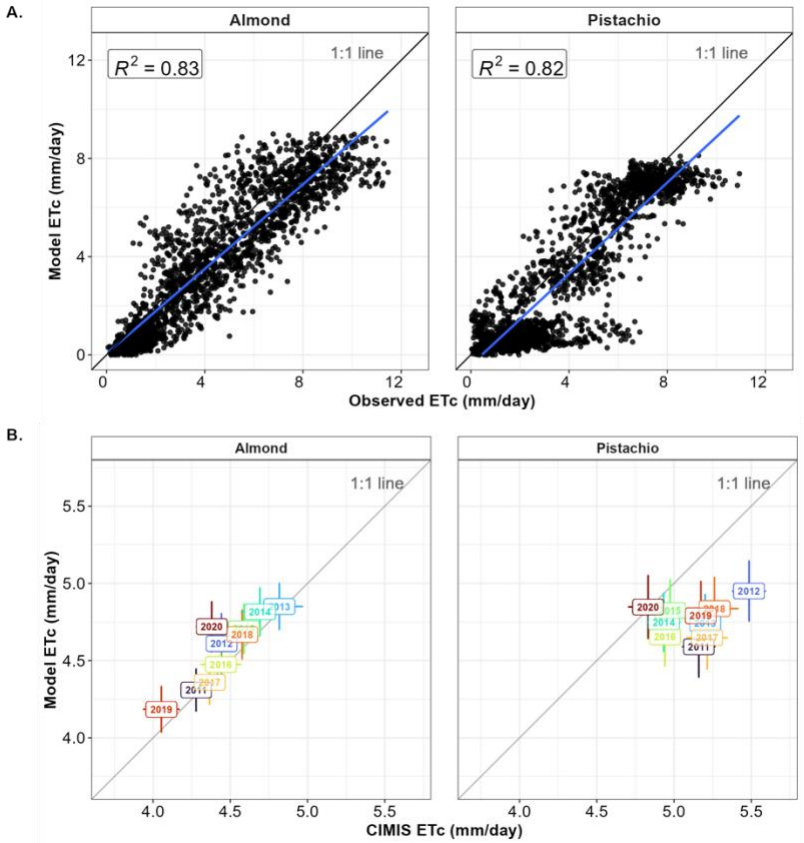


Figure 2.2 Comparisons of modeled ETc with observations from eddy fluxes and CIMIS estimations. A: (top panels): Scatter plot of observed evapotranspiration from Ameriflux eddy covariance flux-tower sites in almond and pistachio orchards versus modeled ETc. B. (bottom panels) Scatter plot of ETc estimations from spatial CIMIS versus modeled results showing yearly average of daily ETc during 2011-2020 years over all grids of respective crops. Horizontal and vertical bars represent one standard deviation in space for both data sources.

2.4.2. Climate change and eCO2 impacts

2.4.2.1. Dormant chilling period

Simulated crop responses to changing climate showed a noticeable difference from the baseline for chill accumulation period and seasonal phenological development stages. The number of days required to accumulate sufficient chilling hours rose for both almonds and pistachios in the climate simulations (2010-2099), with the shift starting earlier under the RCP8.5 scenario (Figure 2.3). In the baseline scenario, on an average, it took 41 days to accumulate 400 chill hours by almonds and 58 days to accumulate 650 chill hours by pistachios. This period was increased to 47 days in RCP4.5 and up to 86 days in RCP8.5 for almonds by the last decade of the 21st century. Similarly, the increases were up to 79 days and 112 days in respective scenarios for pistachios. Pistachio crops were affected more intensely than almonds under both moderate and extreme scenarios.

The fraction of grids that needed to be forced for meeting chill hours requirements for successful bud breaks in the next year were calculated and averaged for the ten-year period. Spatially, the rising number of grids which were forced into budbreak for both crops were observed first in the southern parts of SJV, which are warmer than the central and northern parts (Figure 2.3). Of the total grids covered by almonds, 9% were forced in RCP4.5 and 23% in RCP8.5 by the last decade of the 21st century. In the case of pistachios, 17% of grids were forced in RCP4.5 and 33.6% in

RCP8.5 by 2090-99. A detailed analysis of GCMs revealed that for RCP4.5 scenarios, HadGEM2-ES365 (warm/dry) and MIROC5 (variability) had an earlier surge in areas failing to meet required chill hours, followed by CanESM2 (average) and CNRM-CM5 (cool/wet). Meanwhile, for RCP8.5, the decline was shown earliest in HadGEM2-ES365, followed by CanESM2, CNRM-CM5, and MIROC5.

The end dormancy period dictates the start of the seasonal active growth period, whose deferral could delay the bud break and flowering stages. However, due to the warmer spring season, heat unit accumulation accelerated, leading to the advancement of bud break and flowering earlier in the year (Table 2.2). The average bud break for almonds in the first week of February (DOY 32) under baseline climate conditions advanced by eight days in RCP4.5 but postponed by one day in RCP8.5. On the other hand, the bud break date for pistachios, which occurred in the first week of April (DOY 92) in baseline, advanced by 15 and 11 days in RCP4.5 and RCP8.5, respectively.

Table 2. 2: Summary of dates (DOY) to start phenological stages and active period duration (days) in baseline and their relative changes in climate change scenarios.

Phenological stages' start	**Almond**			**Pistachio**		
	Baseline (DOY)	**RCP4.5**	**RCP8.5**	**Baseline (DOY)**	**RCP4.5**	**RCP8.5**
Budbreak	32	-8	+1	92	-15	-11
Flowering	44	-10	-1	103	-14	-12
Peak LAI	98	-14	-11	164	-14	-14
Filling	72	-12	-7	118	-14	-12
Maturity	245	-21	-23	265	-25	-28
Dormancy	315	+11	+15	315	+11	+15
Stages' cumulative period (in days)						
Maturity (Flowering to Maturity)	200	-11	-21	163	-12	-17
Postharvest (maturity to dormancy)	70	+32	+38	50	+36	+43
Active growth (Budbreak to Dormancy)	283	+19	+13	224	+24	+25

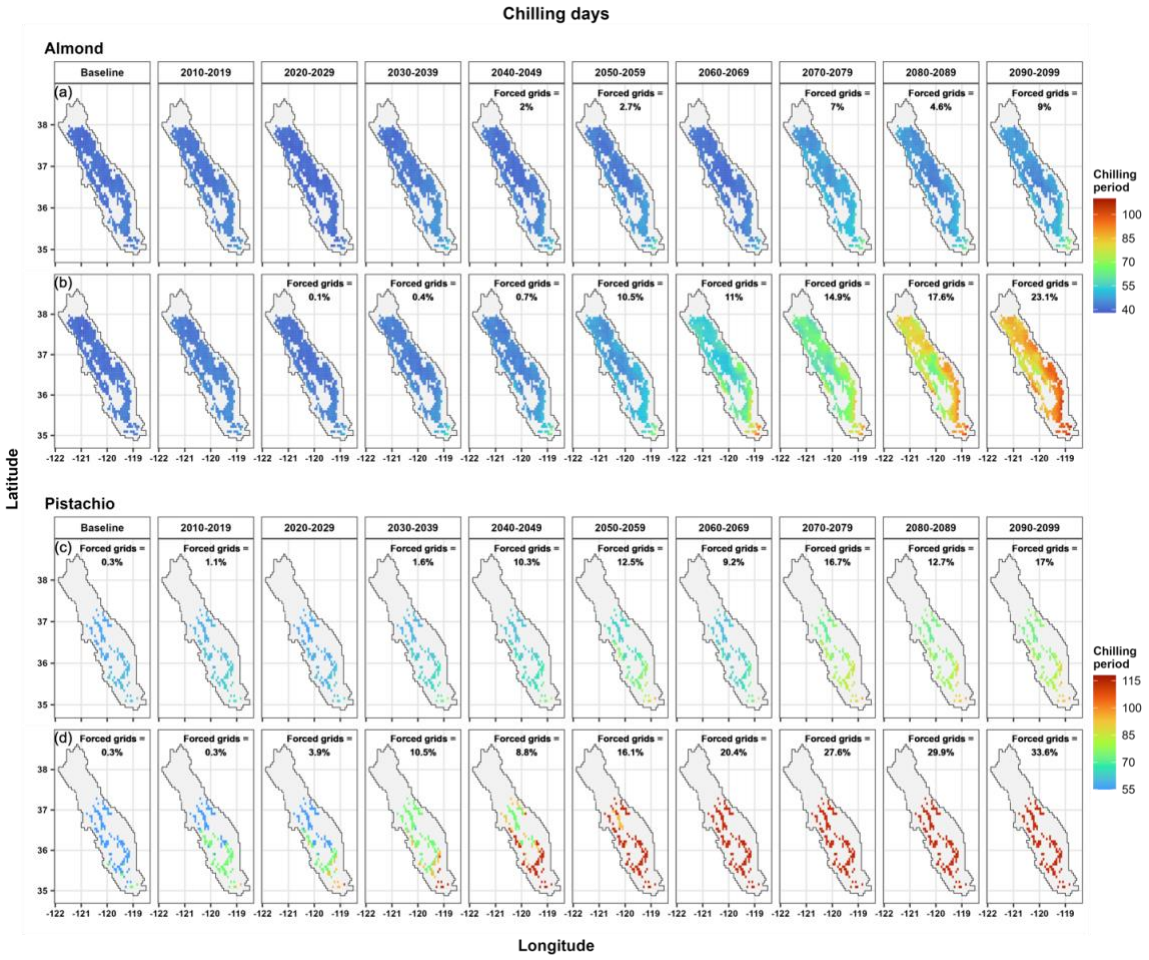


Figure 2.3: Spatial pattern of days to accumulate chill hours for almond (a: RCP4.5; b: RCP8.5) and pistachio (c: RCP4.5; d: RCP8.5) under baseline and climate change scenarios. The forced grids percentage is the average percentage of crop grids that need to be forced for meeting chill hours requirements for successful bud breaks in the next year during the ten-year period.

2.4.2.2. Active growth period

All phenological stages from bud break to maturity for both crops advanced earlier in the active growth period, while the beginning of dormancy postponed in the climate change scenarios (Table 2.2). Overall, the active growth period from bud break to dormancy stretched in both crops under climate change scenarios were compared to the baseline. The average DOY of each stage was modeled based on heat accumulation, so that there were differences between moderate and extreme climate change scenario but no difference among eCO_2 scenarios. Days to flowering, maximum LAI, and nut filling in climate change scenarios were advanced by 10-15 days compared to the baseline. Maturity days were advanced by 20-25 days from the baseline. On the contrary, days to start dormancy, marking the end of active seasonal growth were found to have shifted later in the season in all climate change scenarios.

The average active growth period lengths increased for the whole SJV (Table 2.2). Almond's average maturity period of 200 days (between flowering to maturity days) decreased towards the last decade of the 21st century by 11 days (~6%) and 21 days (~11%) in moderate and extreme scenarios, respectively (Figure 2.4). Similarly, for pistachio, the average 163 days was reduced by 12 days (~7%) and 16 days (~10%) in the respective scenarios. In general, even in the baseline scenario, warmer

regions in the central and southern SJV have shorter maturity periods than the northern by 10-15 days. Due to warming, the maturity period shortening trends were more intense in the southern parts. An opposite trend of increasing number of days was observed in the postharvest period (Table 2.2).

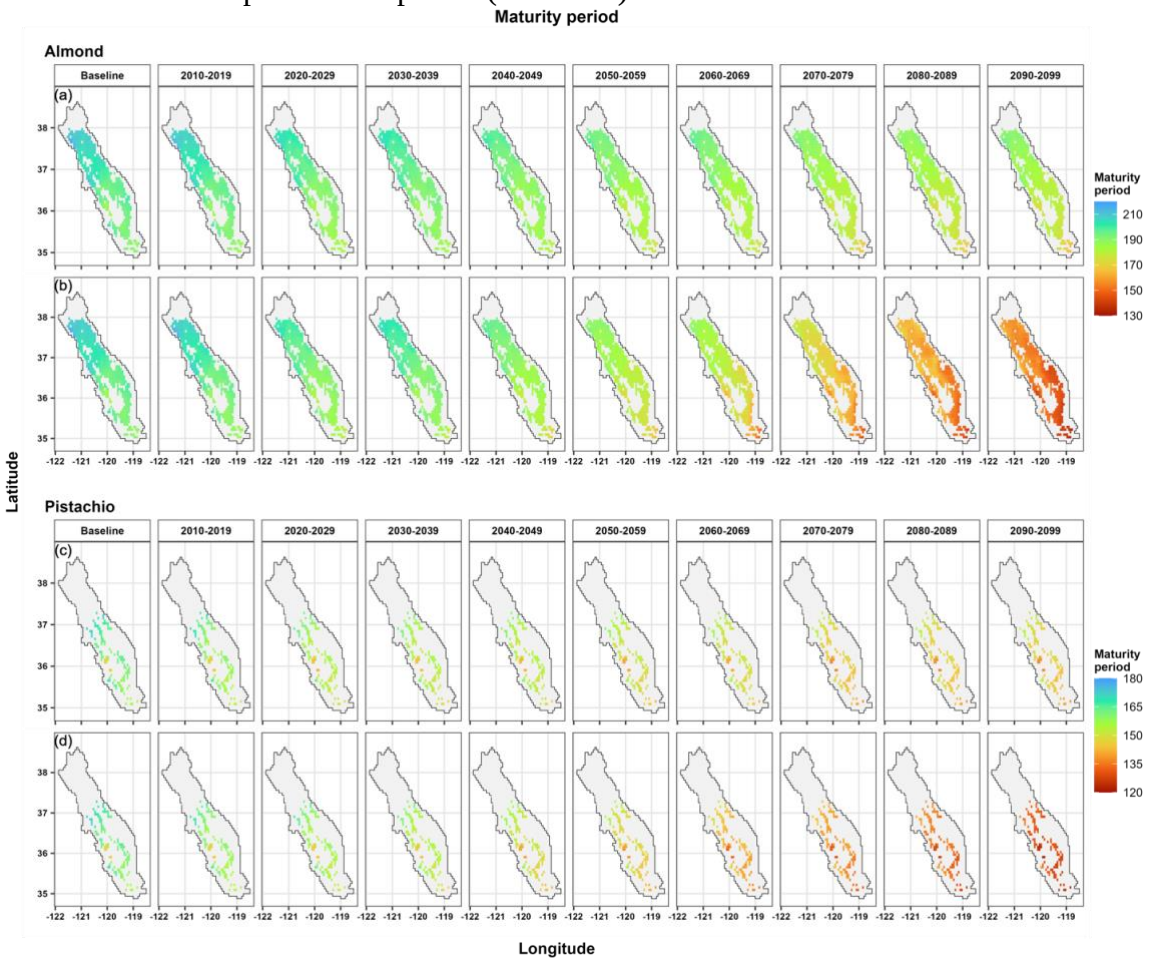


Figure 2.4: Spatial pattern of maturity period (between flowering to maturity days) for almond (a: RCP4.5; b: RCP8.5) and pistachio (c: RCP4.5; d: RCP8.5) under baseline and climate change scenarios.

2.4.2.3. Daily crop water use

Phenological changes, along with warming and eCO_2 led to altered magnitude and timing of crop water use (ETc). Daily crop water use for both crops was found to increase in warming-only scenarios and there were offsetting effects of eCO_2. There were higher variances in these results for both crops in the RCP8.5 scenario, with prominent deviations visible after mid-21st century. Warming-only scenarios results for partitioned daily transpiration (T) and evaporation (E) showed a relatively higher increase in magnitude and earlier shifts in their peak values in active growth season compared to the baseline. Average daily T followed the seasonal shift in phenology and temperature increase. In contrast, E only followed temperature increase (Appendix A Figure S4). The shift in magnitude of T from the baseline under warming + eCO_2 scenarios mainly occurred during the canopy accretion period followed by the peak canopy period (Figure 2.5). Earlier harvest events lowered crop water requirements in the postharvest period, leading to an earlier fall in T curve compared to the baseline. The increase in T magnitude for almonds was more

pronounced in the warming-only scenarios in March-June months, with the highest increase of 0.6 mm/day. For same months, the highest increase in the warming + eCO_2 scenarios were up to 0.4 mm/day. In the case of pistachios, the highest increases were in April-June months, up to 1.2 mm/day in the warming-only and 1.1 mm/day in eCO_2 scenarios. An earlier shift in T was more evident in pistachios in comparison to almonds due to relatively earlier shifts in bud break and peak LAI. In postharvest period, the maximum daily T decrease for almonds was in August, by -0.4 and -0.6 mm/day in warming-only and eCO_2 scenarios, respectively. Similarly, for pistachios the decreases were -0.5 and -0.7 mm/day in warming-only and eCO_2 scenarios, respectively in September. For both crops, eCO_2 scenarios had lower T values than warming-only scenarios.

The overall change in daily ETc fluxes in climate change and eCO_2 scenarios is governed by T, rather than E during the entire growth cycle. The soil and canopy E flux under all scenarios had same seasonal pattern as baseline but showed substantial increase during summer months than baseline scenario (Appendix A Figure S4). ETc increase during summer months coincides with higher atmospheric water demand, critical canopy accrescence and nut filling growth stages, which implies more irrigation requirement. A higher variation in almond ETc can be due to more widespread cultivation in the SJV.

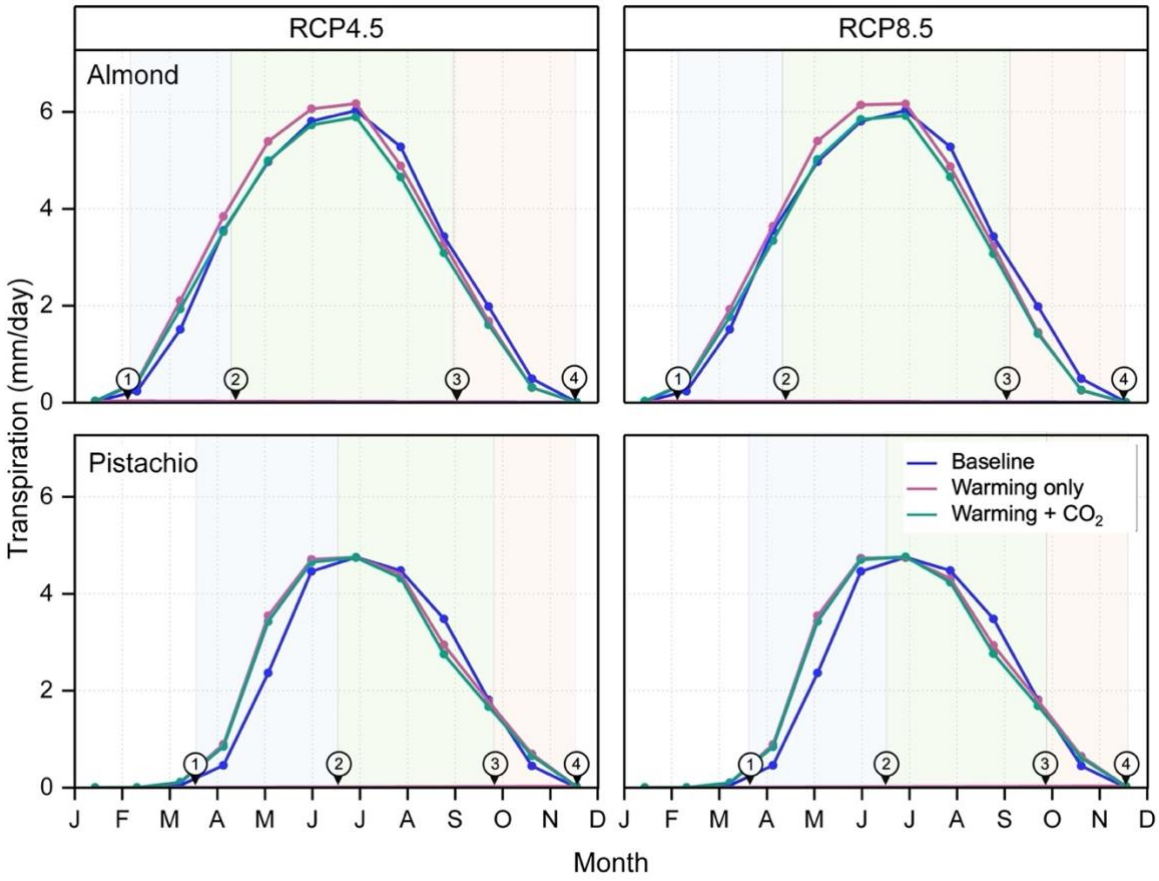


Figure 2.5: Daily transpiration fluxes by months showing the average of baseline (blue), warming-only (magenta), and warming + eCO2 (green) scenarios in RCP4.5 and RCP8.5. Shaded area and numbered points on the x-axis denote traditional baseline phenology dates for the main stages: 1: Flowering, 2: Peak LAI, 3: Harvest, and 4: Dormancy.

Table 2. 3: Average daily ETc (mm/day) with 2 standard deviations (within parentheses) for almond and pistachio crops for baseline and climate change scenarios. The SD values of daily ETc represent variations in both time and space dimensions.

Months	Baseline	RCP4.5		RCP8.5	
		Warming-only	Warming + eCO_2	Warming-only	Warming + eCO_2
Almond					
Jan	0.4 (0.1)	0.4 (0)	0.4 (0)	0.4 (0)	0.4 (0)
Feb	0.9 (0.1)	1.0 (0.1)	1.0 (0.1)	1.0 (0.1)	1.0 (0.1)
Mar	2.3 (0.2)	2.8 (0.3)	2.7 (0.3)	2.7 (0.3)	2.5 (0.3)
Apr	4.4 (0.3)	4.7 (0.2)	4.3 (0.2)	4.4 (0.5)	4.1 (0.4)
May	6.0 (0.3)	6.5 (0.4)	6.1 (0.4)	6.5 (0.4)	6.1 (0.4)
Jun	7.2 (0.3)	7.6 (0.3)	7.3 (0.3)	7.7 (0.2)	7.4 (0.3)
Jul	7.7 (0.2)	8.0 (0.1)	7.7 (0.1)	8.0 (0.2)	7.8 (0.2)
Aug	6.9 (0.2)	6.6 (0.2)	6.4 (0.2)	6.6 (0.3)	6.4 (0.3)
Sep	4.8 (0.2)	4.7 (0.2)	4.5 (0.2)	4.7 (0.3)	4.6 (0.3)
Oct	2.9 (0.2)	2.8 (0.3)	2.7 (0.2)	2.5 (0.4)	2.5 (0.4)
Nov	1.0 (0.1)	0.8 (0.2)	0.8 (0.1)	0.7 (0.2)	0.7 (0.1)
Dec	0.3 (0.1)	0.3 (0)	0.3 (0)	0.3 (0)	0.3 (0)
Pistachio					
Jan	0.4 (0.1)	0.4 (0)	0.4 (0)	0.4 (0)	0.4 (0)
Feb	0.7 (0.1)	0.7 (0.1)	0.7 (0.1)	0.7 (0.1)	0.7 (0.1)
Mar	0.9 (0.1)	1.0 (0.1)	1.0 (0.1)	1.0 (0.1)	1.0 (0.1)
Apr	1.2 (0.3)	1.9 (0.4)	1.9 (0.4)	1.8 (0.4)	1.8 (0.4)
May	4.0 (0.6)	5.4 (0.3)	5.3 (0.3)	5.4 (0.2)	5.3 (0.3)
Jun	6.7 (0.2)	7.0 (0.2)	6.9 (0.2)	7.1 (0.1)	7.1 (0.2)
Jul	7.3 (0.1)	7.4 (0.1)	7.4 (0.1)	7.4 (0.1)	7.4 (0.1)
Aug	6.9 (0.1)	7.0 (0.1)	6.9 (0.1)	6.9 (0.2)	6.8 (0.2)
Sep	5.5 (0.2)	5.0 (0.3)	4.8 (0.2)	5.1 (0.3)	4.9 (0.2)
Oct	3.2 (0.2)	3.2 (0.2)	3.1 (0.2)	3.3 (0.2)	3.1 (0.2)
Nov	1.0 (0.1)	1.2 (0.1)	1.1 (0.1)	1.1 (0.1)	1.1 (0.1)
Dec	0.3 (0.1)	0.4 (0)	0.4 (0)	0.4 (0.1)	0.4 (0)

The analyses of average annual daily crop water use (ETc) during the active growing season showed a gradual increase for almonds but a minor change for pistachios in both warming-only and warming + eCO_2 scenarios (Figure 2.6). On average, the increases in ETc under warming-only scenarios for almonds were 9.5% and 21% in moderate and extreme scenarios from the baseline by the end of the 21st century. The mean increases for pistachios were 1% and 5% in these two warming-only scenarios, respectively. As expected, RCP8.5 scenarios showed greater change in magnitude than RCP4.5. Average daily ETc for almond in the warming + eCO_2 scenarios remained mostly same in the RCP4.5 but increased by 11% in RCP8.5 by the end of the century. However, there were minimal change from the baseline for pistachios in both RCP scenarios. The analysis implies that on an average, almonds

can need up to 1 mm/day of more water throughout the growing season under extreme warming scenario.

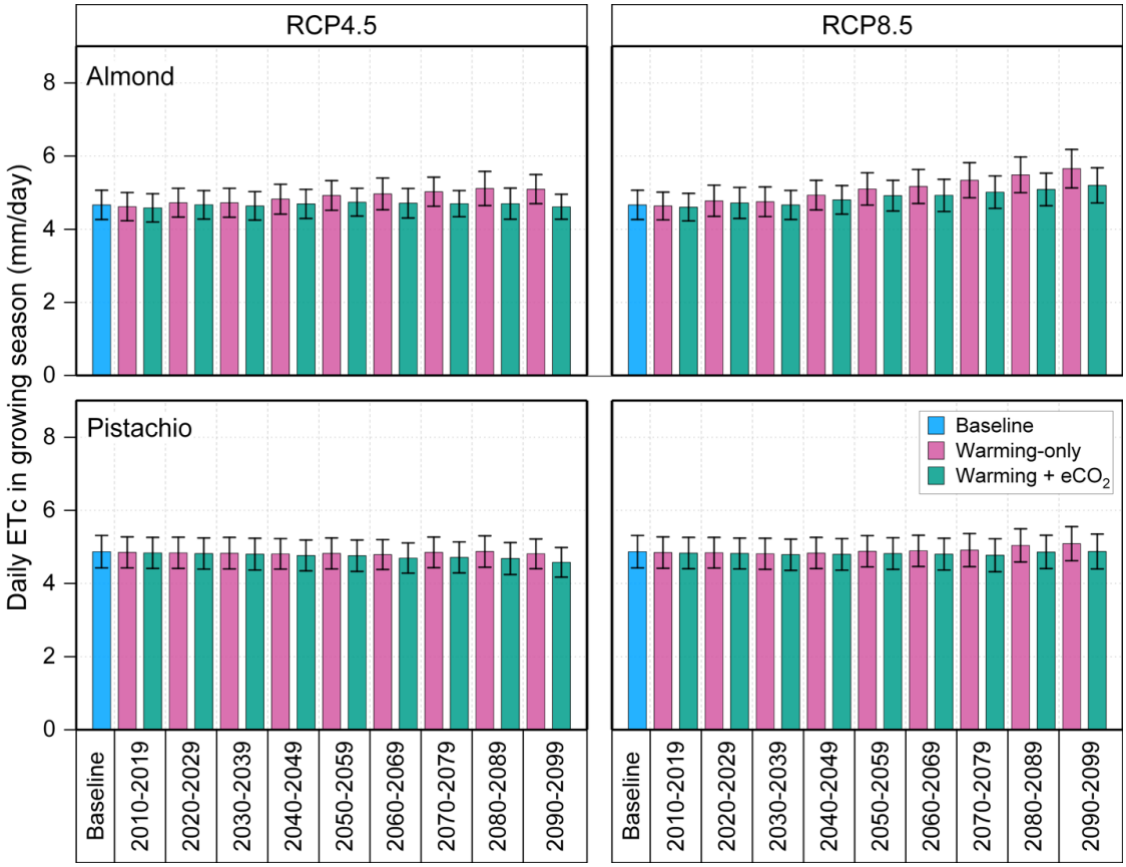


Figure 2.6: Decadal average of daily ETc over the active growing season (i.e., total yearly ETc divided by number of days with LAI>0) under three climate and two CO_2 scenarios for almonds and pistachios. Colored bars show average daily ETc and black error bars show one standard deviation among the GCMs, space (grids) and time (i.e., yearly) from the mean values for each climate scenario and 10-year time period.

2.4.2.4. Cumulative crop water use during major phenological stages

The contracting length of maturity period (i.e., shortening span between flowering to maturity stages) in all warming-only scenarios led to reduced cumulative crop water use in this stage. Similarly, the lengthening postharvest period caused increased water use in this stage (Table 2.2). For the almonds, maturity period shortened by 6% and 11% in RCP4.5 and RCP8.5, respectively, which led to decreased ETc by 5% and 9% in the warming-only scenarios. Similarly, in warming + eCO_2 scenarios, the decrease was 8% and 11% in RCP4.5 and RCP8.5, respectively, during this stage. Meanwhile, almond's postharvest period lengthened by 46% and 54%, which led to ETc increases by 35% in RCP4.5 and 34% in RCP8.5 under warming-only scenarios and increase by 27% in both RCP of eCO_2 scenarios. Overall, baseline cumulative ETc of 1327 mm/year for almonds during the active season increased by 3% and 1% in RCP4.5 and RCP8.5 in warming-only scenarios, respectively (Table 2.4). Under warming + eCO_2 scenarios, however, total ETc during active season, slightly decreased by 2 and 3% under RCP4.5 and RCP8.5, respectively.

Similarly, for pistachios, 7% and 10% decrease in maturity period led to ETc decrease by 4% and 6% under warming-only and 7% and 9% under warming + eCO_2

scenarios in RCP4.5 and RCP8.5, respectively. The differences in annual ETc between RCP4.5 and RCP8.5 warming scenarios were not high due to comparatively shorter maturity period in the latter extreme warming scenarios. Meanwhile 72% and 86% increase in the postharvest period led to an increase in 91% and 110% in respective RCPs of warming-only scenarios and similar changes for warming + eCO_2 scenarios (88% and 105%). The ETc during active growth period increased from 1105 mm/year to around 1200 mm/year (i.e., 8%) in both RCPs under warming scenarios and warming + eCO_2 scenario has similar results (i.e., 6-7%).

Decadal analyses showed dissimilar trends in annual cumulative ETc alterations from the baseline for almonds and pistachios under various climate change and eCO_2 scenarios (Figure 2.7). Under warming-only scenarios, almonds have slight increase by end of the 21st century in RCP4.5, while a slight increase and then, decrease in RCP8.5. There was a minor increase by the mid-century and then, decreasing trend in case of eCO_2 scenarios, which were lower than baseline ETc. Pistachios had higher than baseline ETc in all climate change and eCO_2 scenarios. However, the increased values in the eCO_2 scenarios were lower than the warming scenarios. The modelling results for net annual irrigation requirements showed similar trend as annual ETc.

Table 2. 4: Average cumulative ETc in baseline and relative differences in climate change scenarios.

Cumulative evapotranspiration (mm/year)	**Baseline**	**RCP4.5**		**RCP8.5**	
		Warming-only	**Warming + eCO_2**	**Warming-only**	**Warming + eCO_2**
Almond					
Maturity	1077	-58	-100	-84	-122
Postharvest	253	+88	+68	+86	+68
Active growth	1327	+37	-21	+9	-43
Pistachio					
Maturity	926	-41	-57	-69	-82
Postharvest	146	+133	+129	+160	+154
Active growth	1105	+93	+72	+88	+70



Figure 2.7: Average annual ETc difference from the baseline at decadal period calculated using ETc during the growth period as described in section 2.3.5.

2.5. Discussion

2.5.1. Changing seasonal phenology and daily crop water use

Climate under moderate and extreme climate change scenarios is expected to warm notably. However, warming in the extreme scenario is predicted to be accelerated after the mid-21st century. Warming and added effect of eCO_2, can lead to diverging response by almond and pistachio crops as they show different trends in crop phenology and water use. Deciduous tree crops like almonds and pistachios need to acquire sufficient chill hours in winter to release from endodormancy, followed by heat accumulation to overcome dormancy in spring (Micke, 1996). Almonds requiring lesser chill hours in winter are less likely to be affected by warming winters than pistachios. Warming winters will extend the period for accumulating sufficient chilling hours. This study identified that after acquiring chill hours and dormancy ended following temperature cues in spring, there were earlier advancements in bud break and flowering dates due to warming. Variable winter conditions in SJV can, however, result in unmet chilling hours during the winter dormancy. When chilling conditions were unsatisfactory, practical management such as chemical applications (e.g., Dormex or any other chemical authorized for this type of crops) that force the trees to end dormancy and start bud break/bloom in spring was presumed (assumed on DOY 90). Other dormancy-breaking products and methods can be applied by farm managers to partially compensate for insufficient chill. Examples of such methods are field management to lower heat exposure to flower buds (such as using micro-sprinkler for evaporative cooling, tree vigor, cover crops, and pruning) or applying chemical treatments, horticulture oil, synthetic plant hormones (cytokinins and gibberellins) (Erez, 1995; Jarvis-Shean *et al*., 2021). The simulation results showed that the southern regions of SJV were found to be coerced earlier to fulfill chill accumulation under unmet chilling conditions than northern regions. These instances

were more frequent and widely spread under the warmer RCP8.5 scenario, which led to a delay in spring developmental stages by the end of 21st century (Figure 2.3, Table 2.2). Another phenomenon in winter months is the unusual cooling period and frost damage. One of the ways to protect from frost is application of water on orchard floor (Snyder and Connell, 1996), which can lead to more water consumption and cost to orchard management. However, our analysis showed that the occurrence of frosting days with minimum temperature below 0° C is expected to decline under both climate change scenarios, thus, reducing frost damage threats (Appendix A, Table S2). Additionally, warmer spring, however, was found to shorten the period of heat accumulation for dormancy, which may have counterbalanced the extended chilling period. Thus, there were advancements in both nut crops' bud break and bloom stages.

Simulations from this study revealed a gradual increase in daily transpiration for almonds and pistachios (Figure 2.5). The modelled daily T rates followed the seasonal curve of LAI, having minimal values when trees were dormant in winter, gradually increasing to peak values in summer, and then declining in the postharvest period. Decadal analysis for both crops under the RCP4.5 scenario showed an earlier shift in LAI accretion, followed by an earlier shift in daily T from the baseline towards the end of the 21st century. While under RCP8.5, a distinct LAI trend was observed, i.e., an earlier shift from the baseline till mid-century due to warming springs; then, delays in the latter part of the century due to delayed (forced) bud break due to warming winters and thus, delaying LAI progression closer to the historical baseline. This trend was more evident in the case of pistachios due to higher instances of forced bud breaks.

Moreover, relatively earlier shifts in bud break and peak LAI were estimated for pistachios than almonds (Table 2.2). The magnitude of daily T for both crops were higher during canopy growth than the baseline scenario. T rates in almonds increased more in the warming-only scenarios but was curtailed by partial stomatal closure in response to CO_2 enrichment, showing better water efficiency even with shifted phenology. Pistachios did not respond profoundly to eCO_2 and seemed to have affected by warming more. After nut maturity and harvest, daily T tends to reduce lower than the baseline scenarios for both crops in all scenarios and thus, lowering ETc rates in postharvest periods. This reduction in T was more in the case of pistachios, which may have counterbalanced the increase in maturity phase. Simultaneously, seasonal E rates increased under all scenarios due to rising temperatures, vapor pressure deficits, and atmospheric water demand. Together, they resulted in higher average daily ETc rates. Annual average daily ETc for the growing period can help to anticipate if there is going to be an increase in crops water need for the whole season to prepare accordingly (Figure 2.6). Moreover, an exaggerated response of daily ETc rates and higher variability in time and space was produced under RCP8.5 scenarios compared to RCP4.5.

Spatial analysis showed amplified impacts on the chilling and maturity period for the southern regions of SJV, making them more vulnerable to the changes (Figures 2.4 and 2.5). Unfortunately, both nut crops, especially pistachios, have higher coverage in southern regions (Figure 2.1). The spatial variations in daily T were found to be higher for almonds. A plausible explanation for higher variability is that almond's cultivation is widespread in SJV, adding to higher spatial and climatic diversity than pistachios. In both cases, variations were higher under the RCP8.5 scenario.

2.5.2. Changing irrigation water requirements

The simulation outcomes suggested an earlier shift and higher magnitude of daily ETc during canopy accretion and maturity phases, implying more irrigation requirement in a shorter period. The changes were more pronounced in warming-only scenarios with higher variability in RCP8.5. Canopy growth and biomass accumulation for yield are the internal factors influencing crop water requirements. Under climate change scenarios, there were no change in peak LAI magnitude. However, there were reductions in potential yield (when considering the same management in maximum fruit load) under warming-only and a slight increase in eCO_2 scenarios. Mainly, changing T rates and phenology altered the annual cumulative ETc for the active growing period for almond and pistachio crops. While T rates increase was higher during maturity period, the shorter duration decreased cumulative ETc. On the contrary, lowered T rates, but extended postharvest periods, increased cumulative ETc (Table 2.2). Pistachios experienced more pronounced increase in the postharvest ETc than almonds in both scenarios. ETc is also influenced by atmospheric water demand as represented by increasing E rates. Altogether, almonds responded by slight increase/decrease in annual cumulative ETc under warming-only scenarios, while no change or lowering trend under eCO_2 scenarios. Pistachios' annual ETc was higher than baseline throughout all scenarios with a gradual increasing trend by the mid-century, followed by a constant or decreasing trend under warming-only. Similar trend was found for eCO_2 scenario, but with lesser increase. Both crops showed minor offsetting effect of eCO_2, which agreed with similar results reported for irrigated walnut orchards in Central Valley (Baldocchi and Wong, 2006) and for apples in Washington (Stockle *et al*., 2011).

Net annual irrigation requirements followed similar increasing trend as ETc. Orchard irrigation is dependent on available soil moisture. Soil moisture changes in climate change scenarios are due to changes in soil surface evaporation as well as precipitation amounts and distributions. The total annual precipitation of 260 mm in baseline increased to 285 mm (8%) and 294 mm (12%) in RCP4.5 and RCP8.5, respectively. Seasonal analyses, however, revealed slight decrease in October-December months' precipitation. This decrease was more noticeable in RCP4.5 (-8%) than RCP8.5 scenario (-2%). At the same time, there was an increase in the January-March months values compared to the baseline scenario, with sharper rise in RCP8.5 (21%) than in RCP4.5 scenario (17%). Reduction in the October-December precipitation means extended periods of dry soil in the climate change scenarios. This also implies reduction in soil moisture during elongated postharvest period, resulting in higher irrigation demand. Other studies have also projected increasing future orchard water requirements by almonds (Funes *et al.*, 2021), pistachios (Ahmadi and Baaghideh, 2020), and other Mediterranean crops, e.g., olive (Tanasijevic *et al*., 2014; Knezevic *et al*., 2017) and hazelnut (Vinci *et al*. 2023).

Considering drip irrigation, an average increase of 43 mm/year from the baseline by the mid-21st century (i.e., 2050-59 period) is estimated under RCP4.5 warming-only scenario for almond orchards. This could translate to 2.6 x 10^8 m^3/year (0.21 million acre-feet/year) increase from baseline irrigation under current acreage in SJV (i.e., 26% of total irrigated area). At the same time, an average decrease of 6 mm/year in the eCO_2 scenario could lead to saving 3.5 x 10^7 m^3 (0.03 million acre-feet/year) irrigation water than the baseline. The extent of irrigation increases under warming-only scenarios was higher than the decrease from the added effect of eCO_2 on almond's irrigation till mid-century in both emission scenarios. For same period, an increased irrigation of 80 mm for pistachios can lead to 1.8 x 10^8 m^3/year (0.15

million acre-feet/year) in RCP4.5 warming-only and 1.4 x 10^8 m^3/year (0.11 million acre-feet/year) over baseline irrigation for current acreage (10% of the total irrigated area). The irrigation water saving for pistachios because of eCO_2 was not as prominent as almonds and the projected total irrigation requirements are higher than the baseline in all years and simulation scenarios. However, this analysis did not account for any changes in the irrigation efficiency due to an increase in evaporative losses through droplets under a warmer climate.

Adaptation to climate change impacts will require altering existing irrigation strategy and infrastructure. In our simulations no limitation was set up for irrigation water availability, monetary cost of irrigation system or maintenance. However, in real life, that is not the case. Moreover, providing surface water to ameliorate effects of drought and heat stress events is problematic with existing infrastructure technology and the capacity to cope with more frequent and urgent occurrences is questionable. Currently, groundwater irrigation is used to compensate for abrupt hot/dry drought spells in SJV. However, these unplanned applications may result in less or poor-quality water available during critical stages of crop development of nut filling or bud initiation (Parker *et al*., 2020). These situations can exacerbate the overexploitation of groundwater resources. Furthermore, meeting irrigation demand during an elongated postharvest period can be difficult if most available water is used earlier in the season. Longer and less water-intensive postharvest period provides an opportunity for an adaptive solution of applying deficit irrigation without suffering production losses (Stockle *et al*., 2011; Goldhamer and Beede, 2016; Parker *et al*., 2020), which is already an active area of research in California (Goldhamer and Viveros, 1999; Doll and Shackle, 2015; Doll, 2017).

2.5.3. Change in crop productivity

Aforementioned changes can create uncertainties in managing orchard irrigation, pollination, fertilization other management practices. In warming-only scenarios, simulated potential yield change suggest more pronounced impact on pistachios with gradual reductions from the baseline potential yield in comparison to almonds. The offsetting effect of eCO_2 was also more noticeable for pistachios. In general, the almond's yield did not vary much from the baseline yield of 2,565 kg/ha in warming and eCO_2 scenarios of RCP4.5. However, yield decreased in warming-only (by -300 kg/ha) and warming + eCO_2 (by -40 kg/ha) in RCP8.5 after mid-century. The baseline potential yield of 3,860 kg/haRCP4.5 scenario for pistachios went down in warming-only (by -190 kg/ha) but increased in the presence of eCO_2 (+55 kg/ha) in RCP4.5. In RCP8.5 scenario, there was a large reduction under warming-only (-600 kg/ha) by the end-21st century, while with eCO_2, there was a minor increase in eCO_2 (30 kg/ha) till the mid-century, which then decreased to no change by the end of the century. Higher biomass accumulation due to eCO_2 had an offsetting effect to warming. The offsetting effects were not enough to counter the extreme RCP8.5 scenario warming towards the end of the century for both crops. The average decrease at the orchard level, when scaled to SJV could lead to a larger magnitude loss of productivity, profits, and jobs. Our analysis of climate change and eCO_2 impact on potential yield for both crops showed distinct results, which could be related to the reasons discussed below.

Unusual warming during dormancy can impede chill accumulation, leading to asynchronous male-female flowering, pollination timing, altered vegetative growth, and affected yield (Parker *et al*., 2020). The phenological stages after dormancy for both crops were anticipated to shift earlier in the season due to higher heat accumulation in warmer climate change scenarios. For almonds, initial fruit

development after flowering involving cell differentiation is more sensitive to temperature in February, which steers the rest of the season's developmental process (Tombesi *et al*., 2010). Temperature sufficiency and meeting crop water needs during nuts filling and maturing stages are crucial. In the event of heat and water stress in these stages, the crop yield quality and quantity will be affected (Parker *et al*., 2020). Faster phenological development may also reduce the opportunity for biomass gain before harvest (Stockle *et al*., 2010). Other studies have also reported phenological changes in almonds (Gitea *et al*., 2019; Lorite *et al*., 2020) and pistachio (Kallsen, 2017; Kallsen, 2020; Ahmadi and Baaghideh, 2020; Ahmadi *et al*., 2021; Ghrab *et al*., 2016, 2021). More warmer days and extreme temperatures are expected during mid-late summer in SJV, making crops more susceptible to heat stress. This duration also predisposes to minimum soil moisture storage and limited surface water supply. It is worth noting that the critical nut-filling (embryo dry weight accumulation) for almonds starts in early-May and continues through August (Kester *et al*., 1996) as opposed to late-June through September for pistachio (Ferguson and Kallsen, 2016). Since pistachios are more susceptible to adverse heat and soil-water stress during the early nut-filling stage which raises crop water demand, irrigation monitoring and adaptive scheduling will likely require increased manual or technological innovation.

In the postharvest period, although irrigation is applied to keep plants alive, the extended days will impact the total irrigation demand and crop health. Goldhamer and Viveros (2000) underscored that postharvest irrigation cutoffs resulted in reduced bloom density, fruit set, and yield in the subsequent season, affecting almond crop's productivity more than preharvest irrigation cutoffs. Furthermore, carbohydrates stored in this period also drive the occurrence of healthy leaf buds on the trees in the subsequent year (Kester *et al*., 1996). Some perennial tree studies suggested that flower bud differentiation occurring in the postharvest period, when exposed to warmer temperatures, may aid in carbohydrate and nutrient accumulation for subsequent years (Stockle *et al*., 2010; Greer *et al*., 2002). Thus, managing crop water needs in maturity and postharvest periods is equally vital.

2.5.4. Caveats of the study

VIC-CropSyst model performed satisfactorily in simulating the phenology of the tree crops and their daily water use. Other studies have utilized standalone CropSyst or coupled VIC-CropSyst to simulate and compare irrigation demand in climate change, management, and alternative land use strategies (Chinnayakanahalli *et al.*, 2011; Chen, 2014; Malek *et al.*, 2017; Rajagopalan *et al.*, 2018; Hills *et al.*, 2020; Hall *et al.*, 2022; Scarpare *et al.*, 2022). This integrated land surface-crop model is advantageous for assessing agricultural hydrology as it accounts for the effect of temperature and eCO_2 on crop water use while accounting for seasonal phenology, specific irrigation technology, partitioned water fluxes, and temperature stressors. However, there are practical limitations to entirely model the complex crop growth mechanisms and predicting their adaptive processes with changing environmental factors. The model cannot account for the physiological adaptations by crops against these changing factors. It should be noted that there are underlying uncertainties in simplifying complex plant mechanisms and using modeled input data (soil, climate, landuse, etc.) in our simulations. Moreover, irrigation and harvest depend on other natural and management factors other than climate, which vary by region and resource availability.

Measuring ETc and its partitioned components in the field is difficult and observations are sparsely available at global and regional scales, making it difficult to

strictly validate satellite and land surface model outputs (Lawrence *et al.*, 2007; Stoy *et al.*, 2019). For this study, the slope of the region is low, which does not promote substantial downstream subsurface flow. Moreover, low-volume irrigation systems (drip, micro sprinkler, and the like) frequently apply water, making soil water storage less critical for such systems (Goldhamer, 1996). So, this study focuses on evaporative losses by crop transpiration and evaporation from soil and canopy. Novel approaches for measuring partitioned E and T at the ecosystem level will aid in improving land surface models, remote sensing products, better understanding of hydrologic cycles and their response to climate variability (Stoy *et al.*, 2019). This also holds true for the orchard/farm scale studies.

Lack of empirical data on eCO_2 effects on nut tree crops makes validating the model results difficult for the time being. Experiments and predictions have shown the added effect of increased atmospheric CO_2 on efficient water use and increased yield due to the change in canopy conductance. But the feedback and feedforward mechanisms in future climate at the leaf level are not clear and can further complicate the transpiration response (Baldocchi and Wong, 2006; Stockle *et al.*, 2011; Kirschbaum and McMillan, 2018). For instance, increasing CO_2 enhances biomass production and increase in leaf area, which is likely to raise ETc (Stockle *et al.*, 2011). The extent of response to climate and eCO_2 change is a crop specific phenomenon, especially for orchard trees. Consequently, it is recommended to avoid generalizing results. Specific crops should be studied individually.

2.6. Conclusion

Commercial production of almond and pistachio nuts in Mediterranean climate is reliant of surface and groundwater sources. They have high consumptive water use, which will be under increasing pressure in future due to dwindling water resource and competing water demands from other users. Climate change is expected to intensify their vulnerabilities by altering the environmental factors controlling phenological development and water needs. The aim was to establish a reference point in changing seasonal water needs by perennial tree nut cropping systems in the Mediterranean climate. The current extent of cultivation of almonds and pistachios in SJV California served as a case study. This study evaluated the performance of the VIC-CropSyst model in simulating the crop ETc and then, examined the impact of changed environmental conditions on the phenology and consumptive water use of almond and pistachio crops. The working model was improved to accommodate management adaptations for satisfying chilling hours, irrigation requirements, and potential yield of these crops. We utilized the model's spatial and temporal simulation capability to capture the variability at high resolution within SJV. The modeling simulations anticipated an extended active seasonal growth period and altered timing and magnitude of seasonal crop water use by crops and cumulative annual water consumption. The yield potential is vulnerable to climate variability with the likelihood of increasing occurrences of drought conditions and at a minimum a shift in temperature ranges and periods of intensity. There are evolving artificial techniques to control the dormancy and phenology of crops in the field, which may be beneficial in tackling some of the predicted vulnerabilities.

These results underscore the complex relationship among climate change, water availability, and management in orchards. Almond crops are already more water intensive than pistachio and the results showed even higher increase in almond's average seasonal daily water need in warming climate scenarios. On the

other hand, there were increases in annual ETc for pistachios for all scenarios compared to almonds. In general, an offsetting effect of eCO_2 to warming climate conditions were identified. Pistachios, due to their physiological characteristics may withstand drought conditions better than almonds. Nonetheless, they were found to be more vulnerable due to warming winters and higher susceptibility to hot summers during critical stages, which can affect tree growth, water use, yield, and sustenance. To maintain a similar level of production and socio-economic benefits under current cultivation practices, the change in irrigation demands, as suggested by this study, may require restructuring water deliveries and farm management systems. These findings can help farm and water managers in deciding which crop will be more sustainable and economically viable when devising long-term plans. A proposed adaptation strategy is of choosing crop varieties or alternate crops that can withstand climate variations while maintaining optimum productivity.

2.7. References

1. Abatzoglou, J.T. (2013) 'Development of gridded surface meteorological data for ecological applications and modelling', International Journal of Climatology, 33(1), pp. 121–131. Available at: https://doi.org/10.1002/joc.3413.
2. Abatzoglou, J.T. and Brown, T.J. (2012). 'A comparison of statistical downscaling methods suited for wildfire applications.' International Journal of Climatology, 32, pp. 772-780. Available at: https://doi.org/10.1002/joc.2312
3. Adam, J.C., Stephens, J.C., Chung, S.H., Brady, M.P., Evans, R.D., Kruger, C.E., Lamb, B.K., Liu, M., Stockle, C.O., Vaughan, J.K., Rajagopalan, K., Harrison, J.A., Tague, C.L., Kalyanaraman, A., Chen, Y., Guenther, A., Leung, F.-Y., Leung, L.R., Perleberg, A.B., Yoder, J., Allen, E., Anderson, S., Chandrasekharan, B., Malek, K., Mullis, T., Miller, C., Nergui, T., Poinsatte, J., Reyes, J., Zhu, J., Choate, J.S., Jiang, X., Nelson, R., Yoon, J.-H., Yorgey, G.G., Johnson, K., Chinnayakanahalli, K.J., Hamlet, A.F., Nijssen, B., Walden, V. (2015) 'BioEarth: Envisioning and developing a new regional earth system model to inform natural and agricultural resource management.' Climatic Change 129, pp. 555–571. Available at: https://doi.org/10.1007/s10584-014-1115-2
4. Adam, J.C., Yourek, M.A., Scarpare, F.V., Liu, M., McLarty, S., Asante-Sasu, C., McClure, S., Turk, J., Haller, D., Padowski, J., Deshar, R., Brady, M.P., Rajagopalan, K., Barber, M.E., Weber, R., Hall, S.A., Yorgey, G.G., Whittemore, A., Goodspeed, H.L., Stockle, C.O., Gustine, R.N., Kondal, A., Yoder, J., Kruger, C.E., Deaver, B., Downes, M., Tarbutton, S., Callahan, M., Price, P. Roberts, T., Stephens, J., Valdez, W. (2022). Technical Supplement to the 2021 Columbia River Basin Long-Term Water Supply and Demand Forecast. Publication No. 22-12-001. Washington Department of Ecology, Olympia, WA. 207 pp.
5. Ahmadi, H. and Baaghideh, M. (2020) 'Assessment of anomalies and effects of climate change on reference evapotranspiration and water requirement in pistachio cultivation areas in Iran', *Arabian Journal of Geosciences*, 13(9), p. 332. Available at: https://doi.org/10.1007/s12517-020-05316-8.
6. Ahmadi, H., Baaghideh, M. and Dadashi-Roudbari, A. (2021) 'Climate change impacts on pistachio cultivation areas in Iran: a simulation analysis based on CORDEX-MENA multi-model ensembles', *Theoretical and Applied*

Climatology, 145(1), pp. 109–120. Available at: https://doi.org/10.1007/s00704-021-03614-z.

7. Ainsworth, E.A. and Long, S.P. (2005) 'What have we learned from 15 years of free-air CO 2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO 2', *New Phytologist*, 165(2), pp. 351–372. Available at: https://doi.org/10.1111/j.1469-8137.2004.01224.x.
8. Akita, S. and Moss, D.N. (1973) 'Photosynthetic Responses to CO 2 and Light by Maize and Wheat Leaves Adjusted for Constant Stomatal Apertures 1', *Crop Science*, 13(2), pp. 234–237. Available at: https://doi.org/10.2135/cropsci1973.0011183X001300020025x.
9. Allen, L.H. Plant Responses to rising carbon dioxide and potential interactions with air pollutants. *J. Environ. Qual.* 19, 15–34.
10. Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998) 'Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56.' FAO, Rome, 300, D05109.
11. Anderson, R. (2020a). AmeriFlux AmeriFlux US-PSL USSL San Joaquin Valley Pistachio Low [Data set]. AmeriFlux; USDA-Agricultural Research Service, US Salinity Laboratory. https://doi.org/10.17190/AMF/1617720
12. Anderson, R. (2020b). AmeriFlux US-ASH USSL San Joaquin Valley Almond High Salinity [Data set]. AmeriFlux; USDA-Agricultural Research Service, US Salinity Laboratory. https://doi.org/10.17190/AMF/1634880
13. Anderson, R. (2020c). AmeriFlux US-ASL USSL San Joaquin Valley Almond Low Salinity [Data set]. AmeriFlux; USDA-Agricultural Research Service, US Salinity Laboratory. https://doi.org/10.17190/AMF/1617706
14. Anderson, R. (2020d). AmeriFlux US-ASM USSL San Joaquin Valley Almond Medium Salinity [Data set]. AmeriFlux; USDA-Agricultural Research Service, US Salinity Laboratory. https://doi.org/10.17190/AMF/1617709
15. Anderson, R. (2020e). AmeriFlux US-PSH USSL San Joaquin Valley Pistachio High [Data set]. AmeriFlux; USDA-Agricultural Research Service, US Salinity Laboratory. https://doi.org/10.17190/AMF/1617719
16. Baldocchi D. and Waller E. (2014). 'Winter fog is decreasing in the fruit growing region of the Central Valley of California.' Geophysical Research Letters. 41(9).
17. Baldocchi, D. and Wong, S. (2006) *An Assessment of the Impacts of Future CO_2 and Climate on Californian Agriculture*. RESEARCH CEC-500-2005-187-SF. California Climate Change Center.
18. Bedsworth, L., Cayan, D., Franco, G., Fisher, L., Ziaja, S. (2018). Statewide Summary Report. California's Fourth Climate Change Assessment. California Governor's Office of Planning and Research, Scripps Institution of Oceanography, California Energy Commission, California Public Utilities Commission. Publication number: SUM- CCCA4-2018-013.
19. Bohn, T.J. and Vivoni, E.R. (2019) 'MOD-LSP: MODIS-Based Parameters for Variable Infiltration Capacity (VIC) Model over the Continental US, Mexico, and Southern Canada'. [Dataset]. Zenodo. Available at: https://doi.org/10.5281/ZENODO.2559631.
20. Boote, K.J. *et al.* (2013) 'Putting mechanisms into crop production models', *Plant, Cell & Environment*, 36(9), pp. 1658–1672. Available at: https://doi.org/10.1111/pce.12119.

21. CDFA. (2021). California agricultural statistics review, 2020-2021. Available at: https://www.cdfa.ca.gov/Statistics/PDFs/2020_Ag_Stats_Review.pdf.
22. Chen, Wei-Chih. (2014) 'Assessment of irrigation use on crop yield and water supplies in the Midwestern U.S.' Open Access Dissertations. Paper 241
23. Cherkauer, K. A., Bowling, L. C., & Lettenmaier, D. P. (2003). Variable infiltration capacity cold land process model updates. Global and Planetary Change, 38, 151–159.
24. Chinnayakanahalli, K., Adam, J. C., Stockle, C., Nelson, R., Brady, M., Rajagopalan, K. Barber, M. E.; Dinesh, S.; Malek, K.; Yorgey, G.; Kruger, C.; Marsh, T., Yoder, J. (2011). Incorporating agricultural management into an earth system model for the Pacific Northwest region: Interactions between climate, hydrology, agriculture, and economics. In AGU Fall Meeting Abstracts, Vol. 1, p. 04.
25. Dale E Kester, George C Martin, John M. Labavitch. (1996). Growth and Development. Almond Production Manual. Edited by W.C. Micke Oakland: University of California (System). Division of Agriculture and Natural Resources. UCANR Publications 3364.
26. Doll, D. (2017) 'Pistachio Irrigation: Determining Water Needs and Managing Drought'. 8th Advance in Pistachio Production, Merced, California, 14 November. Available at: https://ucanr.edu/sites/PistachioShortCourse/files/274447.pdf.
27. Doll, D. and Shackel, K. (2015) Drought Tip: Drought Management for California Almonds. University of California, Agriculture and Natural Resources. Available at: https://doi.org/10.3733/ucanr.8515.
28. Durán-Zuazo, V.H. *et al*. (2020) 'Redesigning irrigated almond and pistachio cultivation: implications of a shift towards sustainable intensification', Revista de Ciências Agrárias, 43(nsp2), pp. 24–49. Available at: https://doi.org/10.19084/rca.19651.
29. California Department of Water Resources (DWR). (2022). Spatial CIMIS. Available at: https://catalog.data.gov/dataset/cimis-spatial-eto-maps-bb3e2
30. Erez, A. (1995) 'Means to Compensate for Insufficient Chilling to Improve Bloom and Leafing', Acta Horticulturae, (395), pp. 81–96. Available at: https://doi.org/10.17660/ActaHortic.1995.395.7.
31. Ferguson, L. (2014) 'Botany and Physiology of the Pistachio Tree'. 7th Advances in Pistachio Production – Short Course, 18 November. Available at: https://louiseferguson.ucdavis.edu/sites/g/files/dgvnsk6001/files/inline-files/7.pdf (Accessed: 15 December 2021).
32. Ferguson, L. and Kallsen, C. E. (2016) The Pistachio Tree: Physiology and Botany. In: Ferguson, L. and Haviland, D. R. eds. Pistachio Production Manual. Oakland: University of California (System). Division of Agriculture and Natural Resources. UCANR Publications 3545.
33. Funes, I. *et al*. (2021) 'Modeling impacts of climate change on the water needs and growing cycle of crops in three Mediterranean basins', Agricultural Water Management, 249, p. 106797. Available at: https://doi.org/10.1016/j.agwat.2021.106797.
34. Ghrab M., Ben Mimoun M., Masmoudi M.M., Ben Mechlia N. (2016) Climate change and vulnerability of the pistachio and almond crops in the Mediterranean arid areas. In: Kodad O. (ed.), López Francos A. (ed.), Rovira M. (ed.), Socias i Company R. (ed.). XVI GREMPA Meeting on Almonds and Pistachios. Zaragoza: CIHEAM, p. 247-251

35. Ghrab, M. *et al*. (2022) 'Climate change and viability of fruit tree orchards in arid area', JOURNAL OF OASIS AGRICULTURE AND SUSTAINABLE DEVELOPMENT, 4(2), pp. 1–5. Available at: https://doi.org/10.56027/JOASD.spiss012022.
36. Gitea, M.A. *et al*. (2019) 'Orchard management under the effects of climate change: implications for apple, plum, and almond growing', Environmental Science and Pollution Research, 26(10), pp. 9908–9915. Available at: https://doi.org/10.1007/s11356-019-04214-1.
37. Goldhamer, D. (1996). Irrigation Scheduling. Almond Production Manual. Edited by W.C. Micke Oakland: University of California (System). Division of Agriculture and Natural Resources. UCANR Publications 3364.
38. Goldhamer, D. and Beede R.H. (2016) Irrigation Management. Pistachio Production Manual. Edited by L. Ferguson and D. R. Haviland. Oakland: University of California (System). Division of Agriculture and Natural Resources. UCANR Publications 3545.
39. Goldhamer, D.A. and Viveros, M. (2000) 'Effects of preharvest irrigation cutoff durations and postharvest water deprivation on almond tree performance', *Irrigation Science*, 19(3), pp. 125–131. Available at: https://doi.org/10.1007/s002710000013.
40. Gordon, P.; Duncan, R.; Milliron, L.; Lampinen, B. (2020). 'Field Evaluation of Almond Varieties: A Look at Regional Trial Results through Sixth Leaf.' *West Coast Nut*. September 17. http://www.wcngg.com/2020/09/17/field-evaluation-of-almond-varieties/
41. Greer DH, Wunsche JN, Halligan EA. (2002). 'Influence of postharvest temperatures on leaf gas exchange, carbohydrate reserves and allocations, subsequent budbreak, and fruit yield of Braeburn apple (Malus domestica) trees.' NZ J Crop Hortic Sci 30, pp.175–186
42. Hall, S.A., Adam, J.C., Yourek, M.A., Whittemore, A.M., Yorgey, G.G., Scarpare, F., Liu, M., McLarty, S., Asante-Sasu, C., McClure, S., Turk, J., Haller, D., Padowski, J., Deshar, R., Brady, M.P., Rajagopalan, K., Barber, M.E., Weber, R., Stockle, C.O., Goodspeed, H.L., Gustine, R.N., Kondal, A., Yoder, J., Deaver, B., Downes, M., Tarbutton, S., Callahan, M., Price, P. Roberts, T., Stephens, J., Valdez, W. (2022) Columbia River Basin Long-Term Water Supply and Demand Forecast. 2021 Washington State Legislative Report. Publication No. 21-12-006. Washington Department of Ecology, Olympia, WA. 284 pp.
43. Helalia, S. A., Anderson, R. G., Skaggs, T. H., Jenerette, G. D., Wang, D., & Šimůnek, J. (2021). Impact of Drought and Changing Water Sources on Water Use and Soil Salinity of Almond and Pistachio Orchards: 1. Observations. Soil Systems, 5(3). https://doi.org/10.3390/soilsystems5030050
44. Hatfield, J.L. and Dold, C. (2019) 'Water-Use Efficiency: Advances and Challenges in a Changing Climate', *Frontiers in Plant Science*, 10, p. 103. Available at: https://doi.org/10.3389/fpls.2019.00103.
45. Hills, K., Pruett M., Rajagopalan K., Adam, J. C., Liu, M., Nelson, R., Scarpare, F., Stockle, C. O. (2020) 'Calculation of 2020 Irrigation Depletions for 2020 Level Modified Streamflows'. Washington State University, April 14, 2020. Available at: https://s3.wp.wsu.edu/uploads/sites/2535/2020/09/BPAFinalReport2020.pdf

46. IPCC. (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
47. K. Jarvis-Shean, K. Fort, E. Smith, M. Zwieniecki, G. Marino. 2021. Effectiveness and Mechanisms of Dormancy Breaking Treatments for Walnuts – June 1, 2021-March 31, 2022. https://fruitsandnuts.ucdavis.edu/collaborators/california-walnut-board/reports/2021/effectiveness-and-mechanisms-dormancy-breaking
48. Kallsen, C, Parfitt, D., Maranto, J., Holtz, B. (2017) Pistachio Cultivars in California. *Pistachio Production Short Course 2017*. November 14 – November 16, 2017. Available at: https://ucanr.edu/sites/PistachioShortCourse/files/274438.pdf
49. Kallsen, C. (2020) Unusual Pistachio Tree Bloom and Leaf Canopy Development in Kern County (2020) SJV Trees and Vines. July 22, 2020. Available at: https://www.sjvtandv.com/blog/n6j2iyyc22zrvsinopxc9x8ub2y0lz (Accessed: 20 September 2022).
50. Kallsen, C.E. (2017) 'Temperature-related Variables Associated with Yield of "Kerman" Pistachio in the San Joaquin Valley of California', HortScience, 52(4), pp. 598–605. Available at: https://doi.org/10.21273/HORTSCI11775-17.
51. Kirschbaum, M.U.F. and McMillan, A.M.S. (2018) 'Warming and Elevated CO2 Have Opposing Influences on Transpiration. Which is more Important?', *Current Forestry Reports*, 4(2), pp. 51–71. Available at: https://doi.org/10.1007/s40725-018-0073-8.
52. Knežević, M. *et al*. (2017) 'Impact of climate change on olive growth suitability, water requirements and yield in Montenegro', Italian Journal of Agrometeorology, 2017, pp. 39–52. Available at: https://doi.org/10.19199/2017.2.2038-5625.039.
53. Knipper, K. *et al*. (2023) 'Evaluation of Partitioned Evaporation and Transpiration Estimates within the DisALEXI Modeling Framework over Irrigated Crops in California', Remote Sensing, 15(1), p. 68. Available at: https://doi.org/10.3390/rs15010068.
54. Lampinen, B., Connell, J., & Gradziel, T *et al*. (2016). Field Evaluation of Almond Varieties. University of California. Available at: https://rd.almondboard.com/files/A.2015.15-HORT2-Lampinen.Lampinen.Field%20Evaluation%20of%20Almond%20Varieities.pdf#search=field%20evaluation%20of%20almond%20varieties
55. Lampinen, B., Connell, J., & Gradziel, T, Verdegaal, P., *et al*. (2006). Regional Almond Variety Trials for Cultivar Evaluation in California. *2006 Progress Report.* University of California. Available at: https://ucanr.edu/sites/LampinenLab/files/79978.pdf
56. Lawrence, D.M. *et al*. (2007) 'The Partitioning of Evapotranspiration into Transpiration, Soil Evaporation, and Canopy Evaporation in a GCM: Impacts on Land–Atmosphere Interaction', Journal of Hydrometeorology, 8(4), pp. 862–880. Available at: https://doi.org/10.1175/JHM596.1.
57. Liang, X. *et al*. (1994) 'A simple hydrologically based model of land surface water and energy fluxes for general circulation models', Journal of Geophysical Research, 99(D7), p. 14415. Available at: https://doi.org/10.1029/94JD00483.

58. Lobell, D.B. and Field, C.B. (2011) 'California perennial crops in a changing climate', *Climatic Change*, 109(S1), pp. 317–333. Available at: https://doi.org/10.1007/s10584-011-0303-6.
59. Lorite, I.J., J. M. Cabezas-Luque, Arquero, O., Gabaldón-Leal, C., Santos, C., Rodríguez, A., Ruiz-Ramos, M., Lovera, M. (2020) 'The role of phenology in the climate change impacts and adaptation strategies for tree crops: a case study on almond orchards in Southern Europe', Agricultural and Forest Meteorology, 294, p. 108142. Available at: https://doi.org/10.1016/j.agrformet.2020.108142.
60. Malek, K. *et al*. (2017) 'VIC–CropSyst-v2: A regional-scale modeling platform to simulate the nexus of climate, hydrology, cropping systems, and human decisions', Geoscientific Model Development, 10(8), pp. 3059–3084. Available at: https://doi.org/10.5194/gmd-10-3059-2017.
61. Malek, K. *et al*. (2018) 'Climate change reduces water availability for agriculture by decreasing non-evaporative irrigation losses', Journal of Hydrology, 561, pp. 444–460. Available at: https://doi.org/10.1016/j.jhydrol.2017.11.046.
62. Maurer, E. P., Wood, A. W., Adam, J. C., Lettenmaier, D. P., & Nijssen, B. (2002). A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States. Journal of Climate, 15(22), pp. 3237–3251.
63. Medellín-Azuara, J. *et al.* (2011) 'Economic impacts of climate-related changes to California agriculture', *Climatic Change*, 109(S1), pp. 387–405. Available at: https://doi.org/10.1007/s10584-011-0314-3.
64. Meinshausen, M. *et al.* (2011) 'The RCP greenhouse gas concentrations and their extensions from 1765 to 2300', *Climatic Change*, 109(1–2), pp. 213–241. Available at: https://doi.org/10.1007/s10584-011-0156-z.
65. Micke, W.C. (1996) Almond Production Manual. Oakland: University of California (System). Division of Agriculture and Natural Resources. UCANR Publications 3364.
66. O'Leary, G.J. *et al.* (2015) 'Response of wheat growth, grain yield and water use to elevated CO_2 under a Free-Air CO_2 Enrichment (FACE) experiment and modelling in a semi-arid environment', *Global Change Biology*, 21(7), pp. 2670–2686. Available at: https://doi.org/10.1111/gcb.12830.
67. Parker, L.E. *et al*. (2020) 'Extreme heat effects on perennial crops and strategies for sustaining future production', Plant Science, 295, p. 110397. Available at: https://doi.org/10.1016/j.plantsci.2019.110397.
68. Pathak, T.B. *et al*. (2018) 'Climate Change Trends and Impacts on California Agriculture: A Detailed Review', Agronomy, 8(3), p. 25. Available at: https://doi.org/10.3390/agronomy8030025.
69. Rajagopalan, K., Chinnayakanahalli, K. J., Stockle, C. O., Nelson, R. L., Kruger, C. E., Brady, M. P., *et al*. (2018). Impacts of near-term climate change on irrigation demands and crop yields in the Columbia River basin. Water Resources Research, 54, pp. 2152–2182. https://doi.org/ 10.1002/2017WR020954
70. Richardson, E. A., Seeley, S.D. and Walker, D.R. (1974) 'A Model for Estimating the Completion of Rest for "Redhaven" and "Elberta" Peach Trees1', *HortScience*, 9(4), pp. 331–332. Available at: https://doi.org/10.21273/HORTSCI.9.4.331.

71. Rogers, A., Ainsworth, E.A. and Kammann, C. (2006) 'FACE Value: Perspectives on the Future of Free-Air CO2 Enrichment Studies', in J. Nösberger *et al*. (eds) *Managed Ecosystems and CO2*. Berlin/Heidelberg: Springer-Verlag (Ecological Studies), pp. 431–449. Available at: https://doi.org/10.1007/3-540-31237-4_24.
72. Sadok, W., Lopez, J.R. and Smith, K.P. (2021) 'Transpiration increases under high-temperature stress: Potential mechanisms, trade-offs and prospects for crop resilience in a warming world', *Plant, Cell & Environment*, 44(7), pp. 2102–2116. Available at: https://doi.org/10.1111/pce.13970.
73. Sanden, B. (*2010*). Scientific irrigation scheduling in permanent crops: process, planning, programs & pressure bomb. Kern Irrigation Workshop. Kern Soil & Water Newsletter. 8 April 2010.
74. Sanden, B. (2014). Kern UCCE Almond Irrigation Trial & Field Meeting. Kern Soil & Water Newsletter. 6. June 2014.
75. Scarpare, F.V.; Rajagopalan, K.; Liu, M.; Nelson, R.L.; Stockle, C.O. (2022) Evapotranspiration of Irrigated Crops under Warming and Elevated Atmospheric CO_2: What Is the Direction of Change? *Atmosphere*, 13, 163. https://doi.org/ 10.3390/atmos13020163
76. Siad, S.M. *et al.* (2019) 'A review of coupled hydrologic and crop growth models', *Agricultural Water Management*, 224, p. 105746. Available at: https://doi.org/10.1016/j.agwat.2019.105746.
77. Snyder and Connell. Frost protection. (1996). Almond Production Manual. Edited by W.C. Micke Oakland: University of California (System). Division of Agriculture and Natural Resources. UCANR Publications 3364.
78. Stockle, C., Marsal, J. and Villar, J.M. (2011) 'Impact of climate change on irrigated tree fruit production', *Acta Horticulturae*, 889, pp. 41–52. Available at: https://doi.org/10.17660/ActaHortic.2011.889.2.
79. Stöckle, C.O., Nelson, R.L., Higgins, S. *et al.* (2010) 'Assessment of climate change impact on Eastern Washington agriculture', Climatic Change, 102(1–2), pp. 77–102. Available at: https://doi.org/10.1007/s10584-010-9851-4.
80. Stockle, C.O., Martin, S.A. and Campbell, G.S. (1994) 'CropSyst, a cropping systems simulation model: Water/nitrogen budgets and crop yield', Agricultural Systems, 46(3), pp. 335–359. Available at: https://doi.org/10.1016/0308-521X(94)90006-2.
81. Stoy, P.C. *et al*. (2019) 'Reviews and syntheses: Turning the challenges of partitioning ecosystem evaporation and transpiration into opportunities', Biogeosciences, 16(19), pp. 3747–3775. Available at: https://doi.org/10.5194/bg-16-3747-2019.
82. Tanasijevic, L. *et al*. (2014) 'Impacts of climate change on olive crop evapotranspiration and irrigation requirements in the Mediterranean region', Agricultural Water Management, 144, pp. 54–68. Available at: https://doi.org/10.1016/j.agwat.2014.05.019.
83. Tansey, M. (2018) *Plant Physiological Responses to Atmospheric Forcings Affecting Crop Water Use and Yields: Literature Review and Model Comparisons*. RESEARCH ST-2018-1858-01. Sacramento: Department of the Interior, Bureau of Reclamation, Mid Pacific Region, p. 183. Available at: https://www.usbr.gov/research/.
84. Theodore M. DeJong (1996). Photosynthesis and Respiration. Almond Production Manual. Edited by W.C. Micke Oakland: University of California (System). Division of Agriculture and Natural Resources.

85. Tombesi, S. *et al*. (2010) 'Fruit development in almond is influenced by early Spring temperatures in California', The Journal of Horticultural Science and Biotechnology, 85(4), pp. 317–322. Available at: https://doi.org/10.1080/14620316.2010.11512674.
86. USDA National Agricultural Statistics Service Cropland Data Layer. (2020). Published crop-specific data layer. USDA-NASS, Washington, DC. Available at: https://nassgeodata.gmu.edu/CropScape/.
87. Vinci, A. *et al*. (2023) 'Trend Analysis of Different Climate Parameters and Watering Requirements for Hazelnut in Central Italy Related to Climate Change', Horticulturae, 9. Available at: https://www.mdpi.com/2311-7524/9/5/593 (Accessed: 21 September 2023).
88. Walkinshaw, Mike, A.T. O'Geen, D.E. Beaudette. 2022 "Soil Properties." California Soil Resource Lab, 1 Oct. 2022. Available at: casoilresource.lawr.ucdavis.edu/soil-properties/
89. Zhang, J. and Ranford, T. (2021) 'Identification of Key Periods of Temperature Influence on "Sirora" Pistachio Nut Quality', HortTechnology, 31(3), pp. 266–273. Available at: https://doi.org/10.21273/HORTTECH04760-20.
90. Zhang, Y., Chiew, F.H.S., Peña-Arancibia, J., Sun, F., Li, H., Leuning, R. (2017) 'Global variation of transpiration and soil evaporation and the role of their major climate drivers', *Journal of Geophysical Research: Atmospheres*, 122(13), pp. 6868–6881. Available at: https://doi.org/10.1002/2017JD027025.

CHAPTER 3: RISING AGRICULTURE WATER DEMAND AND SUPPLY GAP IN SAN JOAQUIN VALLEY OF CALIFORNIA

3.1. Abstract

The primary finding of this study suggests that under climate change scenarios, there is likely to be a simultaneous increase in demand and decrease in supply during the summer months in the San Joaquin Valley (SJV) of California. This can lead to water deficit in the system during some of the most critical growth stages. Agricultural practices in the SJV rely heavily on the consistent water supply from the Sierra Nevada snowpack. A comprehensive understanding of evolving patterns in water demand and supply is essential for informed decision-making in building resilience and adapting effectively to these changes. The diverse nature of agriculture in SJV needs careful consideration of their characteristics including source of major demand and supply at hydrologic unit. The most significant increase in monthly water use is projected to occur from March to June (5-28 mm/month, or 5-18% in RCP4.5 and RCP8.5) across early, mid and late periods of 2010-2099 under both climate change scenarios. Water supply patterns are expected to shift significantly, with June's supply is estimated to drop by 40-65% in mid to late periods. Significant increases are expected in January and February, while overall supply is likely to rise from October to April and decrease from May to August. Both perennial and annual crops are vulnerable to the widening of the seasonal demand-supply gap. However, constrictive water requirements for perennial crops will make them more vulnerable to the change. The effect of this gap is expected to differ among hydrologic regions of San Joaquin River Basin and Tulare Lake Basin, necessitating effective management strategy at basin scales. The existing surface storage capacity of the region may prove insufficient in accommodating the changing dynamics. This study evaluates the interrelation of shifting agriculture water demand, supply, and hydrology, which can provide valuable insights into adaptation strategies to navigate through future uncertainties effectively.

3.2. Introduction

Contemporary agriculture in California is technologically advanced which incorporates irrigation infrastructures, precision agriculture techniques, and automation to optimize yields and its resource usage. This system is highly competent and productive, relying heavily on the consistent water supply from the Sierra Nevada snowpack. Under climate change, it is anticipated that there will be alterations in agriculture water demand as well as supply. To adapt and bring resilience to the system, an improved understanding of these changes is essential for informed decision-making.

In California, San Joaquin Valley (SJV) is the most productive agricultural region with high-yielding diverse forage, hay, and specialty crops. SJV represents 22% of the state's irrigated crop acreage (California Water Boards, 2023) and is consistently evolving amid the uncertain water future. Its farming and related industries contribute to SJV's 14% of gross domestic product, 17% of employment, and 19% of revenue (Escriva-Bou, *et al*., 2019). In recent years, SJV's cropping

pattern has shifted towards planting high value and water-intensive crops such as perennial fruit and nut crops (Xue *et al*., 2021). These high value crops require large capital investment, round the year irrigation, and are consequently, more vulnerable to prolonged droughts (Johnson and Cody 2015; Mall and Herman, 2019). The evolving agricultural patterns and practices are projected to increase the total agriculture water use (Wilson *et al*., 2016) and affect the regional hydrological processes including evapotranspiration, surface runoff, and infiltration (Xue *et al*., 2021). Climate change further exacerbates these impacts. Rising temperatures lead to increased evaporative losses, which will further alter the soil water balance, crop water availability, and irrigation practices (Malek et. al, 2018). These altered water requirements for crops will likely disrupt future water availability in the SJV (Moyers *et al*., 2024). Concurrently, the changing climatic factors also pose numerous short- and long-term challenges to the productivity of this sector (Pathak and Stoddard, 2018), through water supply curtailment (Hanak *et al*., 2019) and changing crops' biological response (Stöckle *et al*., 2010). The response of crops, however, differs depending on their type, growth cycles, physiological mechanisms, and management practices (Kang *et al*., 2009; Boote *et al*., 2013). Agriculture being the biggest water user and economic foundation for many communities in the SJV (Bedsworth *et al*., 2018), requires greater consideration for climate impact studies on specific crops. The crops in SJV differ in their variety, growth cycles, economic significance, and vulnerability water availability and climate.

Timely availability of water for agriculture is crucial for its long-term sustenance. SJV's irrigated agriculture relies on local surface water supply from the San Joaquin River and the four major rivers (Kings, Kaweah, Tule, and Kern) draining into the Tulare Lake. The supply is facilitated by the extensive infrastructures diverting local snowmelt water and water imported from the north via Sacramento–San Joaquin Delta (DWR, 2023). The winter precipitation and snowpack accumulated in the Sierra Nevada become runoff in the spring and summer flowing through the streams and stored in built reservoirs for further uses. The amount of precipitation generating overland runoff and baseflow (within the near surface) depends on multiple factors including climate, watershed size, landuse, vegetation, geology, and topography (Mirus and Loague, 2013; USGS, 2018). Additionally, this supply also exhibits a strong seasonal pattern due to varying timing and type of precipitation. The intensity and type of precipitation govern the distribution of runoff, infiltration, and interception by plant surfaces (Mahmood *et al*., 2014). Studies have shown climate change will increase frequency of intense events, rain to snow ratio, and year-to-year variability in California's precipitation (Dettinger *et al*., 2011; Pierce *et al*., 2013; Berg and Hall, 2015; Swain *et al*., 2018; Persad *et al*., 2020). Additionally, snowpack is also projected to decrease under future warming scenarios (Mote *et al*., 2005; Huang *et al*., 2018, Sun *et al*., 2019). Climate warming will lead to accelerated melting of snowpacks during the earlier season, causing a shift in peak streamflow (Stewart *et al*., 2005). Furthermore, the mountain forest evapotranspiration is also expected to increase by 15% by the end of this century, which will reduce runoff for downstream uses (Bales *et al*., 2018). These seasonal shifts in water supply timing and amount will impact the availability of water for agricultural use when the demand is high. Relating these water supply shifts to changes in agricultural water demand in the SJV will aid to identify the agriculture system's vulnerabilities. This necessitates more research to anticipate change in agriculture water supply at regional scale.

A combination of increased agriculture demand and earlier snowmelt is expected to further decrease surface water supply reliability (Hanak and Lund, 2012). San Joaquin basin has been identified among most at risk snowmelt-dependent basin in the world due to earlier snowmelt (Qin *et al.*, 2020). As witnessed during the recent drought of 2012-2016, the contracted surface water supply (Lund *et al*., 2018) intensified the trend of long-term groundwater overdraft (Faunt, 2009) to support agriculture (Marston and Konar, 2017), but still incurred losses (Howitt *et al*., 2014). Additionally, rising competing water requirements for agricultural, urban, and environmental uses had weakened the operational adaptability of California's diverse surface water systems (DWR, 2016a). This competition is going to be compounded in future due to evolving water policy and uncertainties in water availability enforced by climate change (Bedsworth *et al*., 2018). To sustainably manage water, a key step can will be accurate measurement of water usage and supply (Grantham and Viers, 2014), which is inadequately explored at basin scales.

The escalating future water requirements and unpredictability of supply highlights the increasing significance of developing a practical framework for interpreting patterns in water demand and supply. There is lack of studies which integrate climate change impacts on phenological responses, agriculture water demand and timely surface water supply in the SJV. Research on changing response by high acreage specialty crops, such as nuts, fruits and vegetables grown in the SJV is also scarce. These crops require individual considerations due to their physiological distinction and economic importance. This study answers the question of how climate change will impact the seasonal magnitude and timing of agriculture water demand and surface water supply. The objective is to first simulate seasonal water demand by seven major irrigated crops under range of climate and two greenhouse emission scenarios till the end of the 21st century. These crops represent distinct crop groups and account for the majority of agriculture water demand in the SJV. Then, natural and regulated water supply (through reservoir operations) changes are analyzed to assess the climate change induced changes. The water related to crops growth and flexibility of water storage infrastructure at basin scales are studied to understand the system vulnerabilities. The climate change scenarios selected in the study consist of wet-cool, hot-dry, average, and variable climatic conditions. This research will enhance systematic understanding of water dynamics in Mediterranean climate and inform decision makers to prepare for building system resilience.

3.3. Methods

3.3.1. Study area

SJV constitutes the southern part of California's Central Valley. It is part of the San Joaquin River and Tulare Lake Basins. The San Joaquin River is the main drainage channel, flowing northward from the high Sierra Nevada through the valley and eventually draining into the Sacramento–San Joaquin River Delta (Figure 3.1). The San Joaquin River has headwaters in the southcentral Sierra Nevada mountains and is accompanied by its three major tributaries: the Merced, Tuolumne, Stanislaus, and Mokelumne Rivers. Further south in the basin lies Tulare Lake, a freshwater lake fed by the Kings, Kaweah, Tule, and Kern Rivers.

SJV is a flat valley floor bordered by the Coast Ranges to the west and the Sierra Nevada mountains to the east, stretching from the Delta in the north to the Tehachapi Mountains in the south. Its flatness allows for large-scale mechanized farming and the implementation of efficient irrigation systems. The region is

characterized by Mediterranean climate with hot, dry summers and mild, wet winters. Average annual precipitation is around 350 mm, decreasing north to south and typically occurring between November and March. The valley floor is covered in alluvium, a rich and fertile soil deposited by rivers over millennia, and is characterized by a very gentle slope, ideal for large-scale mechanized farming. Land use is dominated by agriculture, while urban areas and natural vegetation like forests and wetlands make up a smaller portion. Approximately 5.7 million acres of irrigated agricultural areas produce a vast range of crop types, including fruits, nuts, vegetables, grains, and hay.

The crops chosen for this study represent diverse crop types (covering percent of irrigated SJV acreage in paratheses): Almonds (26%), grapes (10%), pistachios (10%), winter wheat (7%, "wheat" from henceforth), alfalfa (7%), tomato (3%), and corn (2%) are among the top ten crops grown in the SJV (USDA, 2020). These crops constitute more than 70% of the cumulative crop evapotranspiration, irrigated crop area, and applied water within the eight counties forming part of the SJV (Appendix B Figure S1). The crops were selected based on California Department of Water Resources' (Region Offices) annual estimates of irrigated crop area, crop evapotranspiration, and applied water for 20 crop categories at county level over California (DWR, 2018b, using Cal-SIMETAW model, Orang *et al*, 2013). The crops' acreages were ranked for each of the eight counties forming part of the SJV and were found to be among the top 15 crops in these counties.

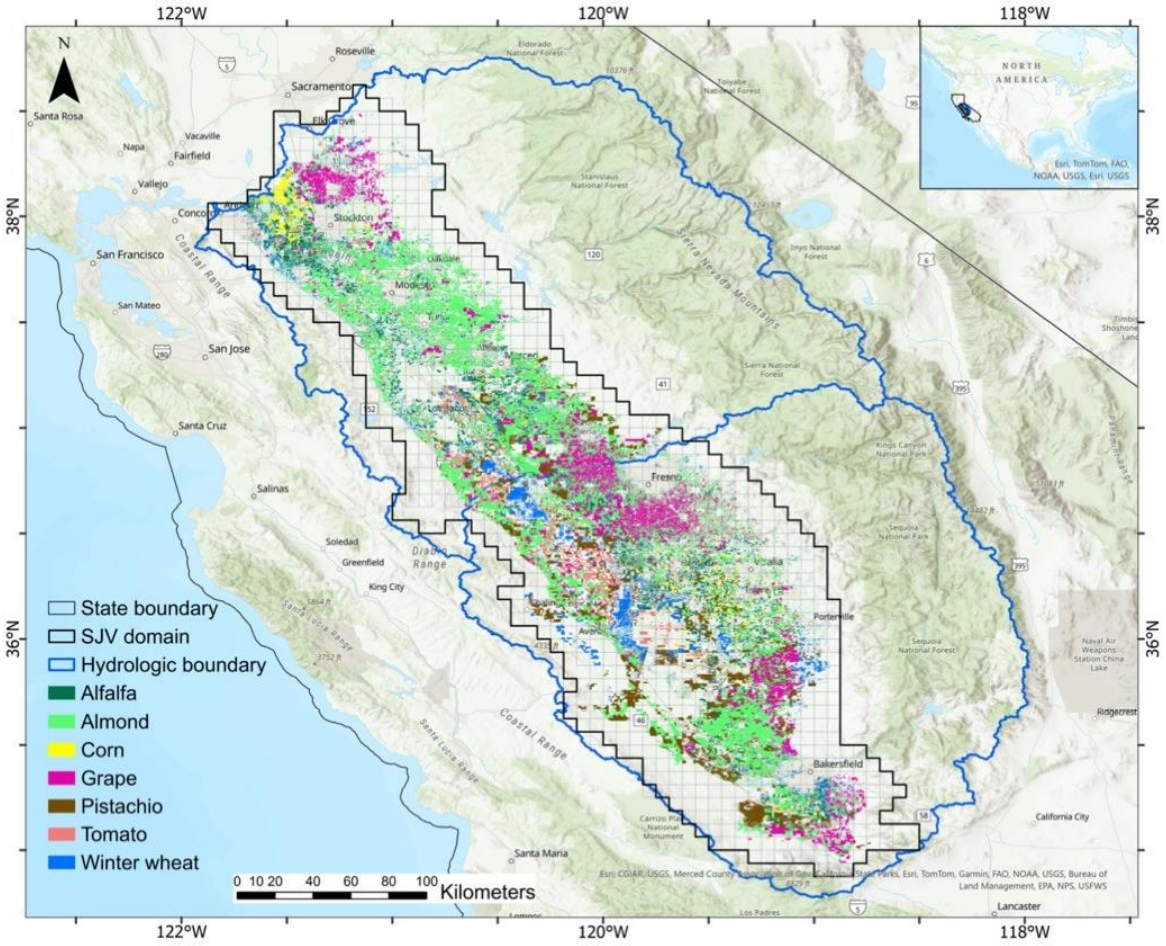


Figure 3.1: Study area map showing SJV boundary (black) with location of 7 crops within the hydrologic regions of San Joaquin (north) and Tulare Lake (south) basins (blue).

3.4.1. VIC-CropSyst Model

This study used a coupled hydrology-crop model, VIC-CropSyst, to estimate the agriculture demand from diverse crop classes. The Variable Infiltration Capacity (VIC) model (Liang *et al*., 1994), a large-scale, process-based water and energy balance model, has been calibrated and utilized for various studies in the Sierra Nevada region of California (Maurer, 2007; Livneh *et al*., 2013; Shukla *et al*., 2015; He *et al*., 2019; Sododerquist and Luce, 2021), including the present study. CropSyst model (Stockle *et al*., 1994) simulates the growth and development of individual crops using their characteristics, irrigation, and planting dates to provide estimates of daily evapotranspiration and biomass as a function of radiation and transpiration use efficiency (Stöckle *et al*., 2003; Scarpare *et al*., 2022). For this study, we utilize the integrated VIC-CropSyst model, which combines these two models to produce simulations of soil water budget, crop phenology, water use, and yield at a 1/16th degree grid scale (~6 km x 6 km). In the integrated model, seasonal phenological stages are determined by the accumulated daily heat units (in growing degree days) using a linear thermal response curve model and effective chilling hours are calculated using the Utah Chilling Unit Model (Richardson *et al*., 1974). This integrated approach has been successfully applied to study the impact of climate change in various agricultural regions, including California (Kandhway *et al*., 2024, in review), Washington, and the Columbia River basin (Malek *et al*., 2018, 2021; Rajagopalan *et al*., 2018; Yourek *et al*., 2023).

3.3.3. Model calibration and validation

The first step in the model calibration was identifying the sensitive parameters for the VIC-CropSyst model, which was compiled from previous studies by Rajagopalan *et al*. (2018), Adam *et al*. (2022), and Kandhway *et al*. (2024, under review). Next step was defining the annual growth length and stages for each crop by adjusting the accumulated heat growing degree-day values within the specified base and cutoff temperatures. For annual crops, fixed planting dates signify the start of yearly seasonal cycles, with harvesting marking the end. The simulated phenological stages for annual crops include flowering, peak leaf area index (LAI), yield filling, maturity, and senescence. For alfalfa crops, phenological stages include leaf emergence, peak LAI, and dormancy. Peak LAI for alfalfa triggered the clipping events (assuming 99% aboveground biomass removal) and dormancy marked the end of seasonal growth cycle. Since alfalfa ETc is calculated in the model from reference ET for which multiple clippings are involved, the total seasonal ETc is underestimated and is lower than the observed ETc. However, the number of seasonal cuttings and daily ETc follow the observed trend. For tree crops, the beginning of the seasonal growth cycles was marked by leaf emergence or bud break, and the end by dormancy. The stages in between included flowering, peak LAI, fruit-filling, maturity, and dormancy. The peak LAI stage also triggered the clipping events for these crops. Thereafter, parameters related to crop evapotranspiration (ETc) such as crop coefficient, canopy coverage, leaf water potential and root depth were specified. Subsequently, yield-related parameter values such as dry yield or maximum fruit load values were updated. For more information on the calibration of tree crops, once can refer to Kandhway *et al*., 2024 (under review) and Appendix B Table S1.

3.3.4. Input data

The VIC-CropSyst model utilizes a variety of input data, including climate, land cover, atmospheric CO_2, soil, crop/vegetation phenology, physiology, and management information. The model was calibrated and validated using gridded climate data from 1980 to 2020 (Abatzoglou, 2013). For projecting future climate changes, the model uses downscaled climate data from the Multivariate Adaptive Constructed Analogs (MACA; Abatzoglou and Brown, 2012) derived from four Global Circulation Models (GCMs) of the Coupled Model Intercomparison Project 5 (CMIP5). The selected GCMs represent a range of climate projections: HadGEM2-ES365 (warm/dry), CNRM-CM5 (cool/wet), CanESM2 (average), and MIROC5 (representing variability across all 10 CMIP5 GCMs recommended in California's Fourth Climate Change Assessment, Bedsworth *et al*., 2018). The model maintains the atmospheric CO_2 concentration at a constant level of 360 ppm. Soil input data for the model were developed using STATSGO2 data, adapted to the model's resolution for textural characteristics, distribution, and hydrology. The calibrated soil parameters were initially based on Maurer *et al*. (2002). To match CropSyst model requirements, these data were subsequently updated using the latest climate averages and by increasing the number of soil layers from 3 to 17 (by dividing the second layer to 15 layers). Land cover data for the SJV boundary was sourced from the USDA-NASS Crop Data Layer (USDA, 2020), available at 30 m spatial resolution. Then, fractional land cover for natural vegetation and crop classes was calculated at each grid. The grids having fractional area cover of 1% of under one or more of the chosen crops were selected for simulation. Monthly LAI for natural vegetation and crops (other than selected 7 crops) were input as fixed values in the vegetation file (from Bohn and Vivoni, 2019).

Most of the model input and calibration parameters related to approximate dates for phenological stages, ETc and crop yield were sourced from California-based field trials, production manuals, published research and reports, and expert communications (DeJong, 1996; Goldhamer, 1996; Kester *et al*., 1996; Micke, 1996; Lampinen *et al.*, 2006; Sanden 2010; Ferguson, 2014; Doll and Shackel, 2015; Goldhamer and Beede, 2016; Ferguson and Kallsen, 2016; Doll, 2017; Kallsen 2017; Kallsen *et al.*, 2017; *Gordon et al*., 2020; Jackson and Williams, 2006; Fulton *et al*., 2006; Howell *et al.*, 2007; Lundy, 2015; Medellin-Azuara *et al.*, 2018; Tim *et al*., 2008; Hanson and May, 2004; Summer and Putnam, 2008; Williams and Ayars, 2005; Hanson *et al*., 2008; Williams *et al*., 2010).

The VIC model simulated average daily runoff (mm/day) and baseflow (mm/day) data at monthly time-step using LOCA downscaled GCMs climate projections are publicly available for download (Cal-Adapt, 2018; Pierce *et al*., 2018). The regulated flow is analyzed by considering the main 13 reservoirs in the San Joaquin and Tulare Lake basins. The name of selected reservoirs are: Pardee Reservoir, New Hogan Lake, New Melones Reservoir, Hetch Hetchy Reservoir, Lake Lloyd/Lake Eleanor, Lake McClure, Hensley Lake, Eastman Lake, Millerton Lake, Pine Flat Reservoir, Lake Kaweah, Lake Success, and Lake Isabella. The monthly data for reservoir inflows and outflows are based on CALVIN model simulations for historical (1950-2000) and future (2040-2090) time periods (Draper et al., 2003; Dogan, 2011; Herman and Giulian, 2018; Li, 2024).

3.3.5. Climate scenarios and analysis

The study compared climate change scenario simulations with the historical baseline to assess alterations in agriculture demand from the San Joaquin Valley (SJV) and

supply by the San Joaquin River and Tulare Lake basins. The experimental scenarios encompassed four Global Circulation Models (GCMs) for three climate scenarios: no climate change (baseline, 1975-2005), moderate change (RCP4.5, 2006-2099), and extreme change (RCP8.5, 2006-2099). A total of eight climate scenario simulations were run for seven crops. The climate change simulations were divided into three 30-year intervals (2010-2039 as early, 2040-2069 as mid, and 2070-2099 as late) to capture the gradual changes over time. The scenario simulations assumed no water stress and maintained consistent crop composition, irrigation, and land use type in the future. Climate variables and crop characteristics were the only factors allowed to change. The period of crop growth considered here include the days when transpiration was greater than zero and exclude dormancy period for perennial crops. All analyses were conducted for the water year, starting in October and ending in September.

The seasonal growth cycle and crop water use were simulated for each scenario using the calibrated and validated VIC-CropSyst model. Initially, changes in seasonal growth length, monthly and annual ETc were analyzed for individual crops. Subsequently, the consumptive water use at the SJV level was calculated by taking the area-weighted average of ETc for present crops at the grid level, for both monthly and annual time steps. This consumptive water use is defined as the agricultural water demand for the study domain (hereafter referred to as "demand"). The sum of runoff and baseflow aggregated at a monthly time-step is defined as the natural local surface water supply (hereafter referred to as "supply"). All the analyses were also spatially summarized for the San Joaquin River and Tulare Lake basins to understand the impact on each hydrologic unit.

3.4. Results

3.4.1. Changes in agricultural demand

3.4.1.1. Crop growth cycle

Under a warming climate, the seasonal growth length within the water year decreased for annual and almond crops, while it increased for alfalfa, pistachio, and grape tree crops compared to baseline (Appendix B Figure S2 and S3). The warming temperature resulted in an accelerated rate of heat accumulation for all crops. The growth length of annual crops decreased by 10-34 days for corn (-22%), wheat (-19%), and tomato (-22%) in the late period of RCP8.5. Conversely, the growth length for alfalfa increased by 18 days (6%) in the same period. The decreasing and increasing trends spanning from the early, mid and late periods of the 21st century across all scenarios were gradual for annual and alfalfa crops.

The growth cycles of tree crops changed for almond, pistachio, and grape differently. Tree crops requiring distinct winter chill hours to break dormancy exhibit relatively complex growth cycles than the annual and perennial alfalfa crops. The warming winters under climate change scenarios delayed the chill accumulating period. This delay will be expected to result in a later bud break for almond, which typically happens in February. In contrast, warmer spring days resulted advanced the bud break for pistachio and grape trees, which typically experience this phase in April and March, respectively. Consequently, the growth length was reduced by 18 days (-6%) for almond but increased by 20 and 17 days (8% and 6%) for pistachio and grape, respectively. An exception was observed for pistachio in the late period of RCP8.5, where bud break is delayed due to forced dormancy. In general, maturity

periods were shortened, and postharvest period were lengthened in the climate change scenarios.

3.4.1.2. Crop water use

The cumulative seasonal water uses for annual crops reduced, while increased for perennial crops compared to the historical baseline across all periods and scenarios (Figure 3.2, Appendix B Table S2). A general trend was the shift of peak crop water demand for all crops earlier in the season (except for alfalfa). The most substantial increases were observed in the months of March, April, and May for all crops (ranging from 15-84 mm/month) (Appendix B Table S3). For annual crops, even with reduced cumulative ETc, the water use was found to be higher than the baseline for a significant portion of the seasonal active growth length when analyzed at monthly scale. For example, corn's total ETc is expected to reduce by 60 mm/year (-9%), but it can have an increase by 56 mm/month in May (+57% of the baseline month) for the late period under RCP4.5. Among perennial crops, alfalfa was found to have a higher ETc than the baseline in almost all months under both scenarios, with the highest increase of 35 mm (55%) in March. Similar, monthly increase during maturity period was assessed for perennial tree crops. For instance, pistachio showed 48 mm increase in water use during the month of May for the late period under RCP4.5. However, both annual and tree crops generally showed signs of reduction in the typical baseline harvest months due to earlier maturity. The values differ for each crop depending on their maturity duration. For instance, in August, corn's ETc can be expected to reduce by 56-66 mm (-70-83%), but there is only up to a 1-4 mm/month decrease (0-2%) for pistachio in the late period of RCP8.5. However, a reduction of 12-14 mm (8%) in September for pistachio can be expected in the same period and scenario.

The cumulative seasonal ETc among annual crops decreased with the most significant reduction for wheat (-190 mm/year, -34%), followed by tomato (-135 mm/year, -18%) and corn (-90 mm/year, -13%) by the late period of RCP8.5. In contrast, the simulated increase for alfalfa from the baseline was 40-110 mm/year (4-11%). For tree crops, the approximate total seasonal ETc increase was 35-85 mm (3-6%) for almond, 60-115 mm (6-10%) for pistachio, and 50-150 mm (6-17%) for grape among all periods and scenarios. There were higher magnitudes of increase or decrease under the extreme scenarios influenced by larger phenological changes. Tree crops, even with shorter maturity period, demonstrated an increase in water use during the maturity period, but a decrease in the post-harvest period.

The simulation results showed similar trend in water use change among the four climate and two greenhouse emission scenarios but varied in magnitude (Appendix B Figure S4). In general, RCP8.5 results were more drastic compared to RCP4.5 across early and mid-periods of all GCM. Minor deviations from the general trends were seen in the late century for perennial crops. In case of annual crops, lesser decreases were estimated for the warmer HadGEM2 and variable MIROC5 compared to CNRM-CM5 and CanESM2. For perennial crops, the results were comparable with across four climate models, with no obvious difference in trends. In most cases, there were higher variability towards the late period of 21st century.

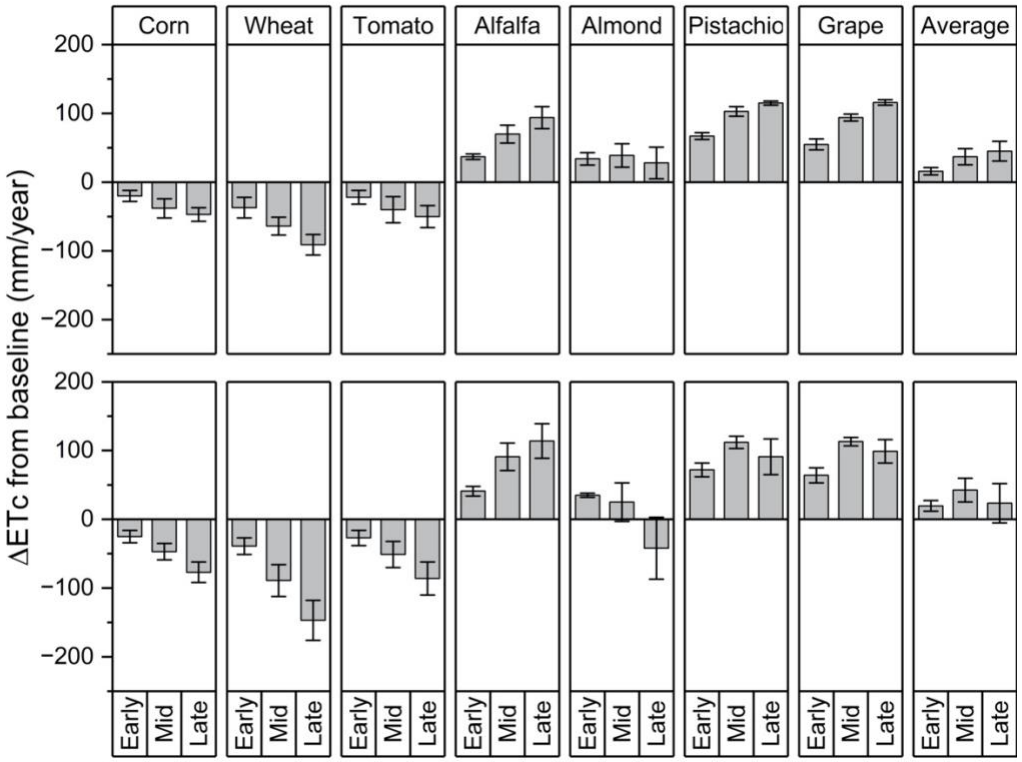


Figure 3.2*:*Crop water demand change from baseline. Difference between the total cumulative ETc from baseline and climate change scenarios for each crop in early, mid and late periods under RCP4.5 and RCP8.5. "Average" is the area weighted average ETc from each crop in a grid, summarized for the whole SJV. Variations among the four selected GCMs are shown as error bars, +/- one standard deviation.

3.4.1.3. Changes in agricultural demand

Climate change simulations for the seasonal cumulative demand for the SJV showed an increase by 4% under both moderate and extreme warming scenarios compared to the baseline value of 1220 mm/year. The increase ranged from 37-68 mm/year across all scenarios (Figure 3.2). In volumetric terms, considering irrigated acreage of seven crops (approximately 70% of 5.1 million acres, DWR, 2018b), implies an increase from 14,300 thousand acre-feet per year (TAF/year) up to 15,100 TAF/year by the end of the 21st century. Historically, about 82% of the demand is attributed to the months of April to September, with monthly demand ranging from 1190 to 2550 TAF/month. The highest magnitude increase was estimated in month of May (Figure 3.3) can add up to 200-320 TAF/month (12 to 18%) to the baseline demand of 1,800 TAF/month in the mid and late periods. This was followed by the second highest increase in June with the addition of up to 200 TAF to the baseline demand of 2,270 TAF/month. The most significant increase in monthly use was estimated to occur from March to June (5-28 mm/month, or 5-18%) across all periods of both scenarios. Notably, the highest increase in consumptive use compared to the baseline happened in March, with an additional demand increases of 100-200 TAF/month (up to 40%). Minor changes (0±3%) were observed in the months of July to September. The monthly mean standard deviation representing year-to-year variation was 44 TAF/month.

Analysis at the hydrologic basin level revealed a slightly higher increase in demand for Tulare Lake Basin than San Joaquin River Basin in the early to mid-century and then vice-versa in the late century. The San Joaquin River Basin baseline

average demand of 5,900 TAF/year can increase by 200-400 TAF/year (3-7%), while that of Tulare Basin can increase from 8,700 TAF/year by 200-385 TAF/year (2-4%). However, in any given climate change scenario and period, the increases in summer month values were higher for the Tulare Lake Basin than those for the San Joaquin Basin (Figure 3.4).

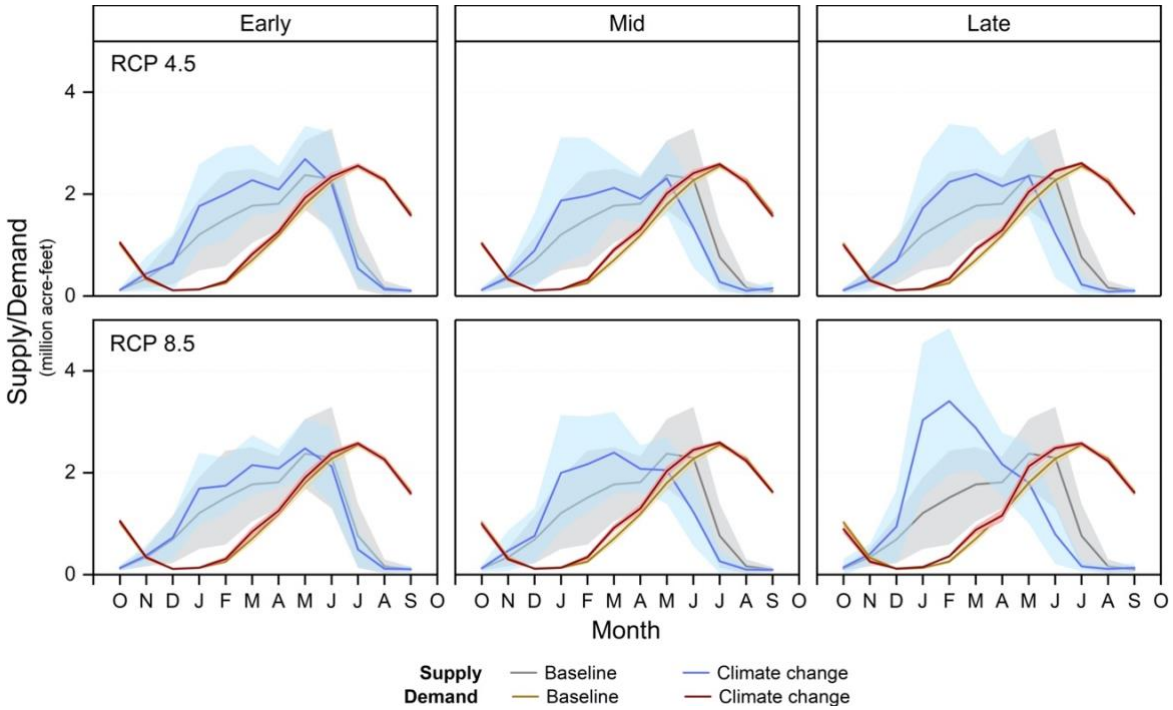


Figure 3.3: Monthly demand from SJV and combined surface water supply from two basins averaged for four GCMs and space (i.e., grids). The brown and dark red lines represent monthly the demand in the water year for baseline and climate change periods (early, mid late) and two emission scenarios (RCP4.5 and RCP 8.5). For all panels grey and blue lines represent the monthly supply. The shaded regions is the standard deviation showing yearly variation for given months and time periods.

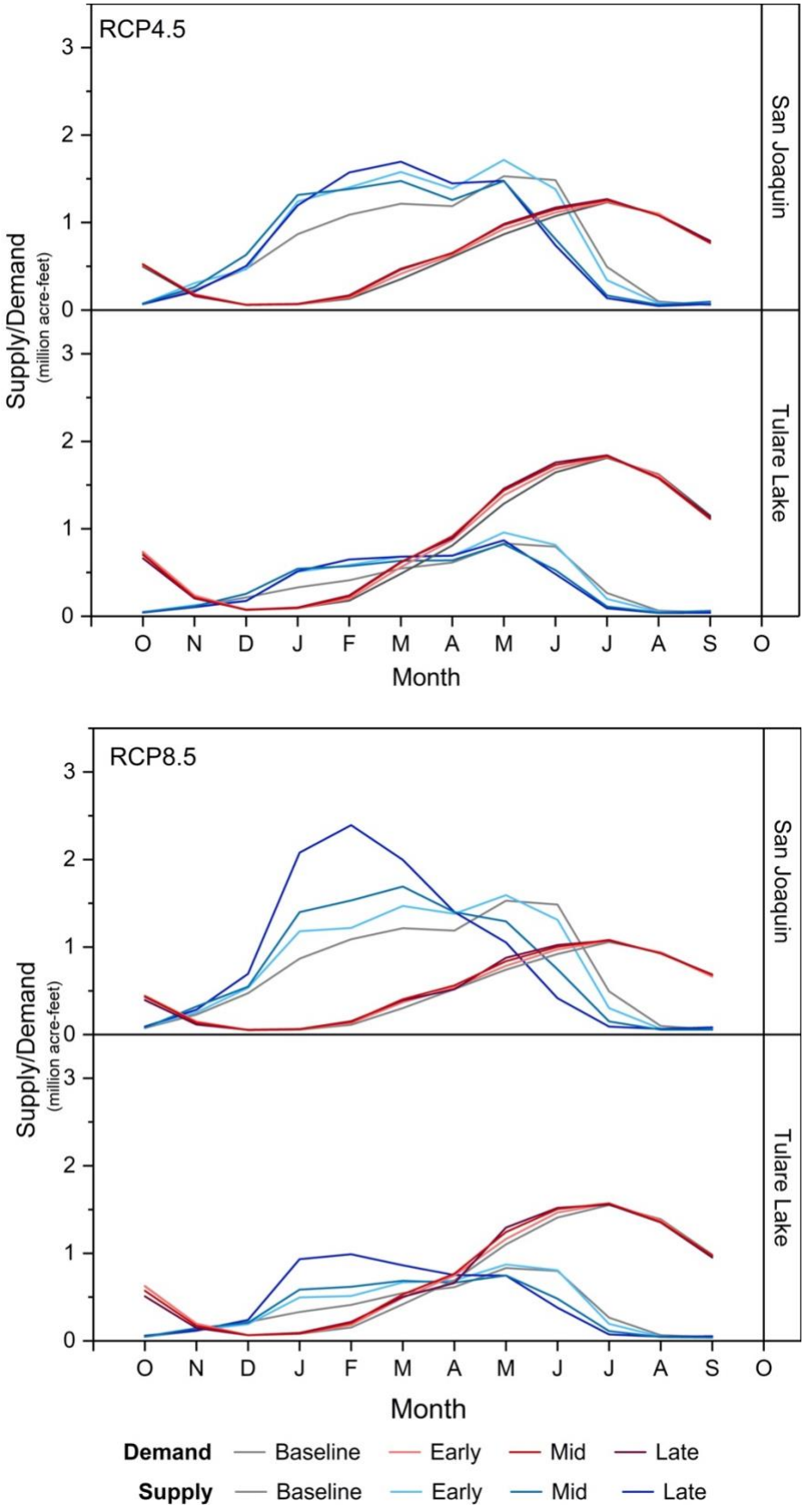


Figure 3.4: Monthly demand from portion of SJV falling in San Joaquin and Tulare Lake basins and monthly surface water supply from each of two basins. The grey and dark red lines represent monthly the demand in the water year for baseline and climate change periods

(early, mid late) and two emission scenarios (RCP4.5 and RCP 8.5). The dark grey and blue lines represent the monthly supply.

3.4.1.4. Changes in surface water supply

The total annual surface water supply for the combined hydrological area is anticipated to increase along with the projected shift in timing (Figure 3.3). Under climate change scenarios, the supply for all periods was found to be higher than the baseline supply of 13,200 TAF/year, ranging from 13,500 to 16,000 TAF/year (2 to 22%). The average increase in RCP8.5 (11%) scenario was higher than RCP4.5 (7%). Historically, about 78% of the annual surface water supply for the study domain is generated from January to June. This proportion is projected to increase to 80-85% under climate change scenarios. The June month, which historically is among the highest supplying months at the rate of 2,300 TAF/month, is expected to reduce to 950-1,500 TAF/year (40-65%) in mid to late periods under both scenarios. The most substantial increases in supply were calculated for January (+500 to 1,800 TAF or 40 to 150%) and February (+200 to 1,900 TAF or 15 to 125%) compared to their baseline values of 1,200 and 1,500 TAF/month, respectively. Overall, an increasing trend in water supply is evident in the months of October to April, while a decreasing trend is observed from May to August, predominantly in mid and later periods. The monthly mean standard deviation representing year-to-year variation was high at 500 TAF/month.

The average cumulative baseline surface water supply generated for the San Joaquin River and Tulare Lake Basin regions were estimated to be 8,800 TAF/year and 4,300 TAF/year, respectively. The highest increases for both regions were observed in the late period of RCP8.5, with 21% for the San Joaquin and 23% for the Tulare Basin. The baseline supply in June is estimated to be 1,500 TAF for the San Joaquin, which had significant reductions by 45 to -72% in the mid to late periods of the climate change scenarios. Similarly, the reduction in June flow (800 TAF) for Tulare was 34 to -53%. The shift in peak flow was more pronounced for the San Joaquin (Figure 3.4).

3.4.1.5. Regulated water supply (reservoir operation)

Surface water supply stored in the reservoirs for delayed release can reduce the gap between summer water demand and natural water supply (Appendix B Figure S5 and Table S4). The natural water inflow to 13 reservoirs in San Joaquin and Tulare Lake Basins is projected to shift earlier in the season from May in baseline to April in mid to late century RCP8.5 scenario. In the baseline scenario, the annual cumulative inflow to 13 reservoirs in historical baseline (1950-2000) is 8,900 TAF/year and cumulative outflow from them was 8,800 TAF per year. The average future projections for the 2040-2090 period under the two climate scenarios from HadGEM2 (hot/dry) and MIROC5 (high variability) models demonstrated reduction for inflow to 5,900 TAF and for outflow to 5,800 TAF, respectively. During the peak demand season (May-October), the additional water of 1,800 TAF is supplied from the reservoirs in historical baseline scenario (July-October). This was estimated to reduce in future scenario to 1,500 TAF (June-October).

3.5. Discussion

3.5.1. Widening demand and supply gap

The simulation results indicated a decrease in water demand by annual crops, contrasted by an increase for perennial crops for all periods and scenarios. The

increasing evaporative demand and changing growth cycles of the crops due to climate warming drives the increase in crop water use. These findings agreed with previous studies carried out for crop water demand on tomato, wheat, alfalfa, almond, pistachio, and walnuts (Saadi *et al*., 2014, Scarpare *et al*., 2022; Baldocchi and Wong, 2006; Stockle *et al*., 2010). However, the increase in average demand of the SJV is not large due to diverging crop-specific responses, wherein some crops were found to have increased seasonal water demand, and some have decreased demand. Other studies posit that ecosystem-level tradeoffs between water loss and photosynthesis under increasing atmospheric CO_2 are potentially large enough to reduce drought impacts, despite the large projected increases in water demand from a warmer atmosphere (Swann *et al*., 2016). In the context of this, the simulations were conducted considering scenarios of increasing atmospheric CO_2 in conjunction with climate change. The average results of demand under these scenarios were found to be closely aligned with those obtained without considering the impact of increased CO_2. Thus, for simplicity of illustration, those results are not presented in this study.

The primary finding of this study suggests that under climate change scenarios, there is likely to be a simultaneous increase in demand and decrease in supply for the study domain during the driest months of the water year. This implies less water will be available when the demand is expected to increase in the summer season (June-September) and an earlier shift in surface water supply. Both annual and perennial crops are vulnerable to widening supply and demand gap in the summer season. The critical reproductive stages of the growth cycle for these crops (except alfalfa) coincides with this period. Water limitation during these critical stages can inevitably result in yield penalties (Sadok *et al*., 2020) and damage crops (Stockle *et al*., 2010; Pathak *et al*., 2018), which will affect the agriculture-dependent dairy and processing industries. While this study models corn and wheat based on grain harvesting growth length, it's important to acknowledge that these crops are also widely utilized as feed crops for the dairy industry. Winter wheat (and similar crops oat, barley etc.) when harvested earlier as silage (before the grain maturity stage) can conveniently escape this water deficit period, but this may not be the case for the summer planted silage corn crops. The increasing precipitation may lead to lesser water requirement for winter-spring crops, but intense events can damage the crops. Perennial crops, despite their high establishment cost and water usage, have expanded in production in the SJV. They need steady water supplies throughout the season and cannot be fallowed, creating a hardening demand effect (Faunt and Sneed, 2015). The expansion decisions made by landowners were not influenced by cost of water supply (Mall and Herman, 2019), but better economic efficiency of water use (Medellín-Azuara *et al*., 2015). Even though tree nuts and fruits have higher revenue per acre and profit than other crops, restriction in water supply and acreage losses will lead to most significant losses in operating income (Sunding and Ronald-Holst, 2020). Because of these reasons, perennial crops may have worsened climate change induced water deficit impacts than the annual crops.

The outcomes of the study highlights that the impacts of climate change will differ across hydrologic basins, even though they fall in the same climatic regime. Relatively, the average temperature in Tulare Basin is higher than San Joaquin, which led to higher demand increase in the summer months till early and mid-periods of both scenarios. For the same reason there was a faster rate of contracting growth cycle in late periods of both scenarios, which led to lower demand in Tulare basin this period. Though the overall increase in demand for San Joaquin and Tulare Basins were similar, but the reduction in supply was larger for the former basin. San Joaquin

Basin having relatively higher dependence on snowmelt water supply is expected to be affected more from the climate change (Stewart *et al*., 2005; Safeeq *et al*., 2012; Pierce *et al*., 2018). Spatially, there are higher acreage of some perennial crops (pistachio and grape) in the Tulare Basin, which may bring higher vulnerability to agriculture in this basin. Hence, effective management can be bolstered by summarizing demand and supply changes at the watershed level, as water planning occurs on this scale.

Agricultural practices in the San Joaquin Valley (SJV) do not directly rely on seasonal surface flow for water supply, rather depend on water deliveries from surface water storage structures. Surface storage, such as reservoirs, provides unique climate change adaptation characteristics that are difficult to achieve with other management strategies. They can absorb the irregularities in climatic events (such as floods and droughts, Şen, 2021) by rapid flood detention, providing flexibility in controlled water release, and facilitate groundwater recharge downstream (DWR, 2016a). It is to be noted that there are 34 reservoirs in San Joaquin and 6 in Tulare Lake basins with a combined capacity of 13,570 TAF. Of the 40 reservoirs, this study analyzed the regulated water supply from 13 major reservoirs, the idea was to demonstrate that reservoir's role in safeguarding water supply during summer months. Even with earlier shift in precipitation and snowmelt in future, the annual outflow-inflow difference is expected to be similar to historical values. The water stored in the reservoirs when released for later use can provide timely buffer during these months and absorb variations in natural water supply. Nonetheless, a key question is: whether these structures will be able to accommodate the earlier surface flow and deliver them during peak demand months? The combined peak storage during the wettest water year of this century (in year 1983) was 10,300 TAF (DWR, 2024). From a simple analysis, under climate change extreme scenario the total supply generation will be 16,000 TAF/year and by excluding 3,330 TAF, i.e., the average outflow to Sacramento-San Joaquin Delta (DWR, 2016b) will result in 11,700 TAF of supply needing local storage. This value is larger than the record stored volume in the reservoirs during the highest runoff year of 1983. Furthermore, the impact of future warming is expected to decrease in the storage capacity of the reservoirs in California due to larger storage taken up by increased winter flooding, leaving less scope for spring and summer snowmelt storage. (Persad *et al*., 2020). If the reserved reservoir capacity for flood control is utilized to store excess runoff during wet seasons by modifying operating rules, that may increase the risk of catastrophic dam overtopping (Persad *et al*., 2020; DRW, 2023). In some cases, water from reservoirs will need to be released earlier in the season when agricultural demand is low. This earlier released water can be diverted for groundwater recharge or beneficial ecosystem use. There is also expectation of reductions in year-to-year carryover storage in Central Valley (of which SJV is a part), will further increasing the drought risk (DWR, 2023). While surface water storage infrastructure offers a viable solution to mitigate future climate variability impacts on agriculture, it is important to remain cautious of its limitations.

In addition to increasing consumptive use by agriculture water, water demand by other sectors are also predicted to increase in future. To get a realistic overview of water demand and supply changes in the region, other sectors are worth discussing. Water demand from urban sector is projected to increase the water consumption due to population increase and urban area development (Wilson et al., 2016). Studies have projected that population increase can in California lead to 1,500 TAF (MAF) under no climate change scenarios (Wilson *et al*., 2016) to an increase of 2,900 TAF under

climate change and current population increase rate (Rayej et al., 2011). More water will be diverted from reservoirs and dams to cater for urban use. Another important sector is ecosystem and environmental flow regimes. With warming climate, there will be higher evaporative losses and warmer water temperature (McEvoy *et al.*, 2020). More quantity of water of low temperature from reservoirs will be diverted to regulate low-flow and high temperature of streams and rivers (Null *et al.*, 2013). Depending on the future situation, a higher priority could be given to safeguarding human and ecosystem needs over commercial agriculture demands. Along with impacting water quantity, climate change also negatively affects water quality in rivers, lakes, and reservoirs. The combination of higher temperatures and the presence of nutrients like nitrates from agricultural land creates the ideal conditions for toxic algae to grow in rivers, lakes, and reservoirs (EPA, 2024). Algal bloom in surface water bodies will affect the aquatic ecosystem health and add cost to the infrastructure maintenance. Water is also wasted by aging canals and irrigation systems through seepage and evaporation before it reaches its intended destination (Martin *et al*., 2020). Therefore, upgrading such infrastructure and storage capacity is crucial for maximizing water use efficiency and minimizing waste. Overall, an increased competition for limited water among sectors along with climate induced challenges of drought and heat stress will add to the vulnerability water supply operations and affecting the sustenance of agriculture system in California.

3.5.2. Implications and adaptations

The simulations from a range of climate scenarios produced consistent and unidirectional results, indicating that the resulting impacts of these changes and the effectiveness of mitigating practices are likely to be similar. Acclimatizing to warmer and drier climate will raise the operational costs of water supply from reservoirs and improved infrastructure (Medellín-Azuara *et al.*, 2008; Herman *et al*., 2018). Addressing climate change by adopting adaptive measures will be helpful, however their effects and efficacy are still uncertain (Challinor *et al*., 2014). The current modeling framework does not simulate impacts of climate change on other systems of infrastructure, groundwater, or water quality, but it is important to contemplate their interconnectedness to explore systematic vulnerabilities and adaptive solutions. By considering several broad sets of systems can help achieve enhanced combined utilization of surface water and groundwater, investments in decentralized groundwater recharge and the capture and reuse of stormwater runoff, offer significant potential for improving water resource adaptability (Hanak *et al*., 2017; DWR, 2023). These strategies can also enhance liquid water storage capacity and facilitate the beneficial use of flood flows (DWR, 2018a).

Increased agriculture water demand in SJV has increased the region's water deficit, further straining the already depleted groundwater (Moyers *et al*., 2024). The groundwater pumping has increased in recent years due to less surface water availability during droughts and changes in land use (Faunt and Sneed, 2015). Over-extraction of groundwater has resulted in detrimental consequences such as land subsidence (Faunt and Sneed, 2015) and water quality issues (Hanak *et al*., 2017). Climate-induced increased crop water demand and irrigation application will exacerbate these issues. The worsened groundwater quality was demonstrated to be influenced by change in soil hydrology, irrigation source (groundwater to snowmelt water) and droughts (Schoups *et al*., 2005). Excessive pumping can also draw up saline water from deeper layers, contaminating freshwater supplies, leads to hard-pan formation, affecting soil productivity and nutrient depletion (Rodriguez and Dufour,

2020). In addition to affecting agriculture, the depletion of groundwater also exacerbates water scarcity issues for smaller rural communities that depend on wells for their potable water supply (Perrone and Jasechko, 2017; Mall and Herman, 2019). Besides, increased evaporative losses due to climate change and efficient irrigation technologies (micro-irrigations) can reduce groundwater recharge, which is crucial for agricultural regions relying on groundwater resources (Malek *et al*., 2018).

Given these challenges, the implementation of the Sustainable Groundwater Management Act (SGMA) serves as a crucial legislative response. It mandates reductions in groundwater pumping, thereby compelling farmers to seek alternative water sources and adopt more efficient practices, supported by incentives. SGMA not only mandates reductions in groundwater pumping but also promotes innovative strategies for sustainable water management, exploration of effective recharge areas and the adoption of practices like Flood-managed aquifer recharge (FloodMAR). These practices, which divert excess surface water to groundwater recharge basins during or before flood events, promise to enhance drought resilience and maintain flood control (Ghasemizade *et al*. 2019). This approach offers more adaptable options for groundwater banking, increasing storage during wet periods and thereby reducing the economic impact of droughts (Kocis and Dahlke, 2017).

Another option is retiring less productive lands from cultivation, which can contribute to a reduction in overall water demand and provide co-benefits on previously irrigated agricultural lands (Butterfield 2017; Stewart *et al*., 2019). The historic drought that occurred from 2012-2016 resulted in a near doubling of fallowed agricultural land in the region (Melton *et al*. 2015). At the peak of the drought, in 2015, farmers in the SJV faced water shortages and fallowed croplands, which led to mild crop revenue losses (Hanak *et al*., 2017). The enactment of the SGMA presents an opportunity to broaden recovery efforts to include the restoration of retired agricultural lands (Stewart *et al*., 2019) through incentives provided by Multibenefit Land Repurposing Program. The program aims to encouraging alternative uses for irrigated lands that could yield benefits for farmers and local communities while enhancing public health and environmental outcomes on fallowed lands (Department of Conservation, 2021). However, the growing trend of planting perennial crops and the high economic loss associated with their fallowing makes landowners less inclined to fallow during water shortages and more willing to invest in alternative water sources (Mall and Herman, 2019). Wheat, which can be grown in the SJV with minimal irrigation (4-8 inches) without crop failure, can serve as an alternative to land fallowing (Paterson *et al*., 2022).

The use of treated wastewater is being considered as a potential substitute for fresh water in the irrigation of crops that are not for human consumption. The utilization of recycled water can lessen water extraction, augment water supply, and reduce energy needs and expenses. Plans are underway to escalate the use of recycled water in California to 1,800 TAF by 2040 (DWR, 2023). The joint use of recycled water and stormwater could considerably boost the proportion of alternative water use in agriculture (Qin and Horvath, 2020). However, their extensive application is restricted by strict regulations, treatment costs, energy consumption and future availability, which might decline due to enhancements in water use efficiency (Qin and Horvath, 2020).

3.5.3. Limitations and future scope

The focus of this study was to evaluate the long-term trends and the findings presented here are average outputs from four GCMs for two emission scenarios.

Though they capture variability and prevents co-variability in climate projections (Hall *et al*., 2024), but when extreme events are considered, the result may have higher variability. Moreover, when increasing interannual variability between wet/dry water years (Persad *et al*., 2020) or drought periods are considered, the water deficit can be expected to further worsen. There was no model uncertainty analysis performed and with the simple representation of crop phenology, transpiration, and hydrology, the simulated results are expected to have uncertainties. The uncertainties in results are also inherited from the input data of climate, soil, landuse etc. A recent study estimated that by adopting water saving practices of efficient irrigation, the water use can be lowered by up to 11% in Central Valley (Boser *et al*., 2024). These developments in irrigation technology and policy impositions, which may improve water efficiency are not included in the analyses. There are also limitations in employing the incentivizes, market and behavioral-driven changes in modelling frameworks (Mahmood *et al*., 2014).

To accurately estimate the agriculture water balance, modeling must occur at the field scale to capture crop type variations and water stress differences (Sorooshian *et al*., 2014). CropSyst is a point-scale model, which takes these considerations into account. Additionally, increased ground-based observations are essential for model validation and performance evaluation, enhancing our understanding of hydrological processes in irrigated agricultural areas (Sorooshian *et al*., 2014). However, lack of observed data to parameterize, calibrate and validate each crop's simulation was one of the biggest challenges of the study. This complicates the modelling of crop level changes and adaptations to cope with climate and environmental changes. The modelling results can be improved with availability of more detailed field data. Besides, there is localized feedback associated with the landuse change to agriculture. For example, agriculture area and irrigation often lead to cooling of the region (Mahmood *et al*., 2014). Regional climate model and analysis of local data in California have shown irrigation-induced cooling effect leading to a long-term decreasing ET trend (Kueppers *et al*., 2007; Sorooshian *et al*., 2014). This can lower the impact of climate warming valuations in agricultural regions. These uncertainties and modeling remarks can be considered for an improved future study.

3.6. Conclusion

Climate change poses risks to the inflexibility of emerging cropping pattern's consumptive water use while simultaneously altering the hydrological processes that supply and distribute water. The implementation of integrated modeling framework in this study brought a holistic understanding of the system and aided in evaluating the interconnectedness of agriculture water demand, supply, climate, and hydrology Linking water supply shifts to changes in agriculture water demand at the basin scale helped to identify the regional vulnerabilities. The study provides an understanding into potential future conditions, aiding water managers in understanding evolving supplies and demands and serves as an initial step toward simulating adaptation and mitigation strategies for creating more resilient agricultural systems in California. The comparison of various crop types provided more information on adaptation opportunities strategies to navigate future uncertainties effectively. Perennial tree crops though were found to be more susceptible, their extended life cycle presents the opportunity to implement long-term management and mitigation strategies. The study also emphasizes the importance of surface water storage infrastructure for mitigating climate variability impacts, although these systems have limitations, particularly as

they face increased pressure from earlier snowmelt and more intense winter precipitation. The diverging water demands between annual and perennial crops, coupled with increased competition from urban and environmental sectors, highlight the need for integrated water management strategies. In conclusion, the study underscores the complex challenges that climate change poses to water management in California's agricultural systems. Going forward, new approaches and model integration that utilizes existing data to encompass projected changes in population, land use changes and other water demands along with changes in surface and groundwater availability will bring holistic picture of the California's water system.

3.7. Reference

1. Abatzoglou, J.T. and Brown, T.J. (2012). 'A comparison of statistical downscaling methods suited for wildfire applications.' International Journal of Climatology, 32, pp. 772-780. Available at: https://doi.org/10.1002/joc.2312.
2. Abatzoglou, J.T., 2013. Development of gridded surface meteorological data for ecological applications and modelling. Int. J. Climatol. 33, 121–131. https://doi.org/10.1002/joc.3413
3. Adam, J.C., Stephens, J.C., Chung, S.H., Brady, M.P., Evans, R.D., Kruger, C.E., Lamb, B.K., Liu, M., Stöckle, C.O., Vaughan, J.K., Rajagopalan, K., Harrison, J.A., Tague, C.L., Kalyanaraman, A., Chen, Y., Guenther, A., Leung, F.-Y., Leung, L.R., Perleberg, A.B., Yoder, J., Allen, E., Anderson, S., Chandrasekharan, B., Malek, K., Mullis, T., Miller, C., Nergui, T., Poinsatte, J., Reyes, J., Zhu, J., Choate, J.S., Jiang, X., Nelson, R., Yoon, J.-H., Yorgey, G.G., Johnson, K., Chinnayakanahalli, K.J., Hamlet, A.F., Nijssen, B., Walden, V., 2015. BioEarth: Envisioning and developing a new regional earth system model to inform natural and agricultural resource management. Climatic Change 129, 555–571. https://doi.org/10.1007/s10584-014-1115-2
4. Adam, J.C., Yourek, M.A., Scarpare, F.V., Liu, M., McLarty, S., Asante-Sasu, C., McClure, S., Turk, J., Haller, D., Padowski, J., Deshar, R., Brady, M.P., Rajagopalan, K., Barber, M.E., Weber, R., Hall, S.A., Yorgey, G.G., Whittemore, A., Goodspeed, H.L., Stockle, C.O., Gustine, R.N., Kondal, A., Yoder, J., Kruger, C.E., Deaver, B., Downes, M., Tarbutton, S., Callahan, M., Price, P. Roberts, T., Stephens, J., Valdez, W. (2022). Technical Supplement to the 2021 Columbia River Basin Long-Term Water Supply and Demand Forecast. Publication No. 22-12-001. Washington Department of Ecology, Olympia, WA. 207 pp.
5. Kandhway, A., Scarpare, F, Liu M., Nelson R., Adam J. C., Anderson, R. G. , Conklin. M. H and Safeeq M. (under review) Water Use Dynamics of Almond and Pistachio Crops in the Mediterranean Region Amid Climate Change.
6. Arlo Richardson, E., Seeley, S.D., Walker, D.R., 1974. A Model for Estimating the Completion of Rest for 'Redhaven' and 'Elberta' Peach Trees1. horts 9, 331–332. https://doi.org/10.21273/HORTSCI.9.4.331
7. Baldocchi, D., Wong, S., 2006. An Assessment of the Impacts of Future CO2 and Climate on Californian Agriculture (RESEARCH No. CEC-500-2005-187-SF). California Climate Change Center.
8. Baldocchi, D., Wong, S., 2006. An Assessment of the Impacts of Future CO2 and Climate on Californian Agriculture (RESEARCH No. CEC-500-2005-187-SF). California Climate Change Center.

9. Bales, R.C., Goulden, M.L., Hunsaker, C.T., Conklin, M.H., Hartsough, P.C., O'Geen, A.T., Hopmans, J.W. and Safeeq, M. (2018) 'Mechanisms controlling the impact of multi-year drought on mountain hydrology', Scientific Reports, 8(1), p. 690. Available at: https://doi.org/10.1038/s41598-017-19007-0.
10. Bedsworth, L., Cayan, D., Franco, G., Fisher, L., Ziaja, S. (2018). Statewide Summary Report. California's Fourth Climate Change Assessment. California Governor's Office of Planning and Research, Scripps Institution of Oceanography, California Energy Commission, California Public Utilities Commission. Publication number: SUM- CCCA4-2018-013.
11. Berg, N. and Hall, A. (2015) 'Increased Interannual Precipitation Extremes over California under Climate Change', Journal of Climate, 28(16), pp. 6324–6334. Available at: https://doi.org/10.1175/JCLI-D-14-00624.1.
12. Bohn, T.J., Vivoni, E.R., 2019. MOD-LSP: MODIS-Based Parameters for Variable Infiltration Capacity (VIC) Model over the Continental US, Mexico, and Southern Canada. https://doi.org/10.5281/ZENODO.2559631
13. Boote, K.J., Jones, J.W., White, J.W., Asseng, S., Lizaso, J.I., 2013. Putting mechanisms into crop production models. Plant Cell & Environment 36, 1658–1672. https://doi.org/10.1111/pce.12119
14. Cal-Adapt. (2018). LOCA Derived Data [GeoTIFF]. LOCA downscaled climate projections from Scripps Institution of Oceanography, UC San Diego, https://cal-adapt.org/
15. California Department of Water Resources (DWR). (2022). Spatial CIMIS. Available at: https://catalog.data.gov/dataset/cimis-spatial-eto-maps-bb3e2
16. California Department of Water Resources (DWR). (2016a). Surface Storage — Regional/Local A Resource Management Strategy of the California Water Plan
17. California Department of Water Resources (DWR). (2016b) Estimates of Natural and Unimpaired Flows for the Central Valley of California: Water Years 1922-2014. rep. Available at: https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/california_waterfix/exhibits/docs/ccc_cccwa/part2_surrebuttal/CCC-SC_75.pdf
18. California Department of Water Resources (DWR). (2018) California Water Plan Update 2018. rep. Available at: https://water.ca.gov/Programs/California-Water-Plan
19. California Department of Water Resources (DWR). (2023) California Water Plan Update 2023. rep. Available at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/California-Water-Plan/Docs/Update2023/Final/California-Water-Plan-Update-2023.pdf.
20. California Department of Water Resources (DWR). 2018b. Cal-SIMETAW Unit Values. https://data.cnra.ca.gov/dataset/46c9d40b-fbb5-4ea0-9437-f84138d0b966/resource/dea8ef15-c3ed-4c18-a129-85a99f0a657f/download/calsimetawunitetdata_2018-08-02_publish.csv
21. California Department of Water Resources (DWR). 2024. Reservoir Water Storage (By Hydrologic Region) Report generated: July 12, 2024 07:33. Available at: https://cdec.water.ca.gov/reportapp/javareports?name=STORAGEW
22. Das, T., Dettinger, M.D., Cayan, D.R., Hidalgo, H.G., 2011. Potential increase in floods in California's Sierra Nevada under future climate projections. Climatic Change 109, 71–94. https://doi.org/10.1007/s10584-011-0298-z
23. David, S. and Roland-Holst, D. (2020) 'SJV-Blueprint-for-Extinction-Economic-Study-2-15-2020.pdf'. Water Blueprint. Available at:

https://waterblueprintca.com/wp-content/uploads/2021/09/Blueprint.EIA_.PhaseOne.2.28-v41.pdf.
24. Dogan, M.S. (2011) *Integrated water operations in California: Hydropower, overdraft, and climate change - ProQuest*. Available at: https://www.proquest.com/docview/1738859865?pq-origsite=gscholar&fromopenview=true&sourcetype=Dissertations%20&%20Theses (Accessed: 14 August 2024).
25. Doll, D., 2017. Pistachio Irrigation: Determining Water Needs and Managing Drought.
26. Doll, D., Shackel, K., 2015. Drought Tip: Drought Management for California Almonds. University of California, Agriculture and Natural Resources. https://doi.org/10.3733/ucanr.8515
27. Faunt, C.C. and Sneed, M. (2015) 'Water Availability and Subsidence in California's Central Valley', San Francisco Estuary and Watershed Science, 13(3). Available at: https://doi.org/10.15447/sfews.2015v13iss3art4.
28. Faunt, C.C., ed., (2009), Groundwater Availability of the Central Valley Aquifer, California: U.S. Geological Survey Professional Paper 1766, 225 p.
29. Ferguson, L. (2014) 'Botany and Physiology of the Pistachio Tree'. 7th Advances in Pistachio Production - Short Course, 18 November. Available at: https://louiseferguson.ucdavis.edu/sites/g/files/dgvnsk6001/files/inline-files/7.pdf (Accessed: 15 December 2021).
30. Ferguson, L. and Kallsen, C. E. (2016) The Pistachio Tree: Physiology and Botany. In: Ferguson, L. and Haviland, D. R. eds. Pistachio Production Manual. Oakland: University of California (System). Division of Agriculture and Natural Resources. UCANR Publications 3545.
31. Fulton, A., Bali K., Mousli Z., Jackson, L. (2006). Small Grain Production Manual Part 5 Irrigation and Water Relations
32. Goldhamer, D. (1996). Irrigation Scheduling. Almond Production Manual. Edited by W.C. Micke Oakland: University of California (System). Division of Agriculture and Natural Resources. UCANR Publications 3364.
33. Goldhamer, D. and Beede R.H. (2016) Irrigation Management. Pistachio Production Manual. Edited by L. Ferguson and D. R. Haviland. Oakland: University of California (System). Division of Agriculture and Natural Resources. UCANR Publications 3545.
34. Gordon, P.; Duncan, R.; Milliron, L.; Lampinen, B. (2020). 'Field Evaluation of Almond Varieties: A Look at Regional Trial Results through Sixth Leaf.' West Coast Nut. September 17. http://www.wcngg.com/2020/09/17/field-evaluation-of-almond-varieties/
35. Grantham, T.E., Viers, J.H., 2014. 100 years of California's water rights system: patterns, trends and uncertainty. Environ. Res. Lett. 9, 084012. https://doi.org/10.1088/1748-9326/9/8/084012
36. Grantham, T.E., Viers, J.H., 2014. 100 years of California's water rights system: patterns, trends and uncertainty. Environ. Res. Lett. 9, 084012. https://doi.org/10.1088/1748-9326/9/8/084012
37. Hanak, E. and Lund, J.R. (2012) 'Adapting California's water management to climate change', *Climatic Change*, 111(1), pp. 17–44. Available at: https://doi.org/10.1007/s10584-011-0241-3.
38. Hanak, E., Escriva-Bou, A., Gray, B., Green, S., Harter, T., Jezdimirovic, J., Lund, J., Medellín-Azuara, J., Moyle, P., Seavy, N., 2019. Water and the Future of the San Joaquin Valley: Overview. Available at:

https://www.ppic.org/publication/water-and-the-future-of-the-san-joaquin-valley/.
39. Hanson, B. and May, D. (2004) 'Effect of subsurface drip irrigation on processing tomato yield, water table depth, soil salinity, and profitability', Agricultural Water Management, 68(1), pp. 1–17. Available at: https://doi.org/10.1016/j.agwat.2004.03.003.
40. Hanson, B., Bali, K., Orloff, S., Sanden, B. and Putnam, D. (2008) 'How Much Water Does Alfalfa Really Need?', in. Alfalfa Symposium, Davis, CA, USA. Available at: https://alfalfasymposium.ucdavis.edu/+symposium/proceedings/2008/08-265.pdf.
41. He, M., Russo, M., Anderson, M., Fickenscher, P., Whitin, B., Schwarz, A. and Lynn, E. (2018) 'Changes in Extremes of Temperature, Precipitation, and Runoff in California's Central Valley During 1949–2010', Hydrology, 5(1), p. 1. Available at: https://doi.org/10.3390/hydrology5010001.
42. Herman, J.D. and Giuliani, M. (2018) 'Policy tree optimization for threshold-based water resources management over multiple timescales', *Environmental Modelling & Software*, 99, pp. 39–51. Available at: https://doi.org/10.1016/j.envsoft.2017.09.016.
43. Herman, J., M. Fefer, M. Dogan, M. Jenkins, J. Medellín-Azuara, J. Lund. (2018). Advancing Hydro-Economic Optimization to Identify Vulnerabilities and Adaptation Opportunities in California's Water System. California's Fourth Climate Change Assessment, California Natural Resources Agency. Publication number: CCCA4-CNRA-2018-016.
44. Howell, T.A., Tolk, J.A., Evett, S.R., Copeland, K.S. and Dusek, D.A. (2007) 'EVAPOTRANSPIRATION OF DEFICIT IRRIGATED SORGHUM AND WINTER', in. USCID Fourth International Conference. Available at: https://hdl.handle.net/10217/208252.
45. Howitt, R.E., Medellin-Azuara, J., MacEwan, D., Lund, J.R. and Sumner, D.A. (2014). Economic Analysis of the 2014 Drought for California Agriculture. Center for Watershed Sciences, University of California, Davis, California. 20p. Available at
46. Huang, X., Hall, A.D., Berg, N., 2018. Anthropogenic Warming Impacts on Today's Sierra Nevada Snowpack and Flood Risk. Geophysical Research Letters 45, 6215–6222. https://doi.org/10.1029/2018GL077432
47. Jackson, L and Williams J. (2006) Growth and Delvelopment of Small grians. Small Grain Production Manual, 2006. Pub. 8208, https://anrcatalog.ucanr.edu/pdf/8208.pdf
48. Kallsen, C.E. (2017) 'Temperature-related Variables Associated with Yield of "Kerman" Pistachio in the San Joaquin Valley of California', HortScience, 52(4), pp. 598–605. Available at: https://doi.org/10.21273/HORTSCI11775-17.
49. Kang, Y., Khan, S. and Ma, X. (2009) 'Climate change impacts on crop yield, crop water productivity and food security – A review', Progress in Natural Science, 19(12), pp. 1665–1674. Available at: https://doi.org/10.1016/j.pnsc.2009.08.001.
50. Kester D, George C Martin, John M. Labavitch. (1996). Growth and Development. Almond Production Manual. Edited by W.C. Micke Oakland: University of California (System). Division of Agriculture and Natural Resources. UCANR Publications 3364.

51. Lampinen, B., Connell, J., & Gradziel, T, Verdegaal, P., et al. (2006). Regional Almond Variety Trials for Cultivar Evaluation in California. 2006 Progress Report. University of California. Available at: https://ucanr.edu/sites/LampinenLab/files/79978.pdf
52. Li, L. (2024). *Integrated Agricultural Water and Land Use Management for Conserving Water, Carbon, and Avian Biodiversity Under Climate Change: A Synthesis Approach* (PhD Dissertation).
53. Liang, X., Lettenmaier, D.P., Wood, E.F., Burges, S.J., 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J. Geophys. Res. 99, 14415. https://doi.org/10.1029/94JD00483
54. Liang, X., Lettenmaier, D.P., Wood, E.F., Burges, S.J., 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J. Geophys. Res. 99, 14415. https://doi.org/10.1029/94JD00483
55. Livneh, B., Rosenberg, E.A., Lin, C., Nijssen, B., Mishra, V., Andreadis, K.M., Maurer, E.P. and Lettenmaier, D.P. (2013) 'A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Update and Extensions', Journal of Climate, 26(23), pp. 9384–9392. Available at: https://doi.org/10.1175/JCLI-D-12-00508.1.
56. Lund, J., Medellin-Azuara, J., Durand, J. and Stone, K. (2018) 'Lessons from California's 2012–2016 Drought', Journal of Water Resources Planning and Management, 144(10), p. 04018067. Available at: https://doi.org/10.1061/(ASCE)WR.1943-5452.0000984.
57. Lundy, M. (2015) Drought Tip: Managing Irrigated Corn during Drought. University of California, Agriculture and Natural Resources. Available at: https://doi.org/10.3733/ucanr.8551.
58. M. DeJong, Theodore (1996). Photosynthesis and Respiration. Almond Production Manual. Edited by W.C. Micke Oakland: University of California (System). Division of Agriculture and Natural Resources.
59. Mahmood, R., Pielke, R.A., Hubbard, K.G., Niyogi, D., Dirmeyer, P.A., McAlpine, C., Carleton, A.M., Hale, R., Gameda, S., Beltrán-Przekurat, A., Baker, B., McNider, R., Legates, D.R., Shepherd, M., Du, J., Blanken, P.D., Frauenfeld, O.W., Nair, U.S., Fall, S., 2014. Land cover changes and their biogeophysical effects on climate. Intl Journal of Climatology 34, 929–953. https://doi.org/10.1002/joc.3736
60. Malek, K., Adam, J., Yoder, J., Givens, J., Stockle, C., Brady, M., Karimi, T., Rajagopalan, K., Liu, M. and Reed, P. (2021) 'Impacts of irrigation efficiency on water-dependent sectors are heavily controlled by region-specific institutions and infrastructures', Journal of Environmental Management, 300, p. 113731. Available at: https://doi.org/10.1016/j.jenvman.2021.113731.
61. Malek, K., Adam, J.C., Stöckle, C.O., Peters, R.T., 2018. Climate change reduces water availability for agriculture by decreasing non-evaporative irrigation losses. Journal of Hydrology 561, 444–460. https://doi.org/10.1016/j.jhydrol.2017.11.046
62. Mall, N.K., Herman, J.D., 2019. Water shortage risks from perennial crop expansion in California's Central Valley. Environ. Res. Lett. 14, 104014. https://doi.org/10.1088/1748-9326/ab4035
63. Marston, L. and Konar, M. (2017) 'Drought impacts to water footprints and virtual water transfers of the C entral V alley of C alifornia', Water Resources

Research, 53(7), pp. 5756–5773. Available at: https://doi.org/10.1002/2016WR020251.
64. Martin, P.L., Goodhue, R.E., Wright, B. and Giannini Foundation of Agricultural Economics (eds) (2020) California agriculture: dimensions and issues. Berkeley, California: University of California, Giannini Foundation of Agricultural Economics, Division of Agriculture and Natural Resources (Giannini Foundation information series, 20–01). Available at: https://s.giannini.ucop.edu/uploads/pub/2021/01/26/chapter_1_introduction_2020.pdf.
65. Maurer, E. P., Wood, A. W., Adam, J. C., Lettenmaier, D. P., & Nijssen, B. (2002). A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States. Journal of Climate, 15(22), pp. 3237–3251.
66. Maurer, E.P. (2007). "Uncertainty in Hydrologic Impacts of Climate Change in the Sierra Nevada, California under Two Emissions Scenarios." Climatic Change 82(3–4): 309–25. https:// doi.org/10.1007/s10584- 006-9180-.9
67. McEvoy, D.J., Pierce, D.W., Kalansky, J.F., Cayan, D.R. and Abatzoglou, J.T. (2020) 'Projected Changes in Reference Evapotranspiration in California and Nevada: Implications for Drought and Wildland Fire Danger', *Earth's Future*, 8(11), p. e2020EF001736. Available at: https://doi.org/10.1029/2020EF001736.
68. Medellín-Azuara, J., Harou, J.J., Olivares, M.A., Madani, K., Lund, J.R., Howitt, R.E., Tanaka, S.K., Jenkins, M.W. and Zhu, T. (2008) 'Adaptability and adaptations of California's water supply system to dry climate warming', *Climatic Change*, 87(S1), pp. 75–90. Available at: https://doi.org/10.1007/s10584-007-9355-z.
69. Medellín-Azuara, J., MacEwan, D., Howitt, R.E., Koruakos, G., Dogrul, E.C., Brush, C.F., Kadir, T.N., Harter, T., Melton, F. and Lund, J.R. (2015) 'Hydro-economic analysis of groundwater pumping for irrigated agriculture in California's Central Valley, USA', Hydrogeology Journal, 23(6), pp. 1205–1216. Available at: https://doi.org/10.1007/s10040-015-1283-9.
70. Medellín-Azuara, J., Paw U, K.T., Jin, Y. Jankowski, J., Bell, A.M., Kent, E., Clay, J., Wong, A., Alexander, N., Santos, N., Badillo, J., Hart, Q., Leinfelder-Miles, M., Merz, J., Lund, J.R., Anderson, A., Anderson, M., Chen, Y., Edgar, D., Eching, S., Freiberg, S., Gong, R., Guzmán, A., Howes, D., Johnson, L., Kadir, T., Lambert, J.J., Liang, L., Little, C., Melton, F., Metz, M., Morandé, J.A., Orang, M., Pyles, R.D., Post, K., Rosevelt, C., Sarreshteh, S., Snyder, R.L., Trezza, R., Temegsen, B., Viers, J.H. (2018). A Comparative Study for Estimating Crop Evapotranspiration in the Sacramento-San Joaquin Delta. Center for Watershed Sciences, University of California Davis. https://watershed.ucdavis.edu/project/delta-e
71. Micke, W.C. (1996) Almond Production Manual. Oakland: University of California (System). Division of Agriculture and Natural Resources. UCANR Publications 3364.
72. Mirus, B.B., Loague, K., 2013. How runoff begins (and ends): Characterizing hydrologic response at the catchment scale. Water Resources Research 49, 2987–3006. https://doi.org/10.1002/wrcr.20218
73. Mote, P.W., Hamlet, A.F., Clark, M.P. and Lettenmaier, D.P. (2005) 'Declining Mountain Snowpack In Western North America', Bulletin of the American Meteorological Society, 86(1), pp. 39–50. Available at: https://doi.org/10.1175/BAMS-86-1-39.

74. Moyers, K., Abatzoglou, J.T., Escriva-Bou, A., Medellín-Azuara, J., Viers, J.H., 2024. An invisible water surcharge: Climate warming increases crop water demand in the San Joaquin Valley's groundwater-dependent irrigated agriculture. PLOS Water 3, e0000184. https://doi.org/10.1371/journal.pwat.0000184
75. Null, S.E., Ligare, S.T. and Viers, J.H. (2013) 'A Method to Consider Whether Dams Mitigate Climate Change Effects on Stream Temperatures', *JAWRA Journal of the American Water Resources Association*, 49(6), pp. 1456–1472. Available at: https://doi.org/10.1111/jawr.12102.
76. Pathak, T. B. et al. "Climate Change Trends and Impacts on California Agriculture: A Detailed Review." Agronomy 8.3 (2018): 1–27. Web.
77. Pathak, T.B. and Stoddard, C.S. (2018) 'Climate change effects on the processing tomato growing season in California using growing degree day model', Modeling Earth Systems and Environment, 4(2), pp. 765–775. Available at: https://doi.org/10.1007/s40808-018-0460-y.
78. Persad, G.G., Swain, D.L., Kouba, C., Ortiz-Partida, J.P., 2020. Inter-model agreement on projected shifts in California hydroclimate characteristics critical to water management. Climatic Change 162, 1493–1513. https://doi.org/10.1007/s10584-020-02882-4
79. Pierce, D.W., Das, T., Cayan, D.R., Maurer, E.P., Miller, N.L., Bao, Y., Kanamitsu, M., Yoshimura, K., Snyder, M.A., Sloan, L.C., Franco, G. and Tyree, M. (2013) 'Probabilistic estimates of future changes in California temperature and precipitation using statistical and dynamical downscaling', Climate Dynamics, 40(3–4), pp. 839–856. Available at: https://doi.org/10.1007/s00382-012-1337-9.
80. Qin, Y., Abatzoglou, J.T., Siebert, S., Huning, L.S., AghaKouchak, A., Mankin, J.S., Hong, C., Tong, D., Davis, S.J., Mueller, N.D., 2020. Agricultural risks from changing snowmelt. Nat. Clim. Chang. 10, 459–465. https://doi.org/10.1038/s41558-020-0746-8
81. Rajagopalan, K., Chinnayakanahalli, K.J., Stockle, C.O., Nelson, R.L., Kruger, C.E., Brady, M.P., Malek, K., Dinesh, S.T., Barber, M.E., Hamlet, A.F., Yorgey, G.G., Adam, J.C., 2018. Impacts of Near-Term Climate Change on Irrigation Demands and Crop Yields in the Columbia River Basin. Water Resources Research 54, 2152–2182. https://doi.org/10.1002/2017WR020954
82. Rayej, M., Juricich, R., Groves, D. and Yates, D. (2011) 'Scenarios of Future California Water Demand through 2050: Growth and Climate Change', in *World Environmental and Water Resources Congress 2011*. *World Environmental and Water Resources Congress 2011*, Palm Springs, California, United States: American Society of Civil Engineers, pp. 4423–4432. Available at: https://doi.org/10.1061/41173(414)460.
83. Saadi, S., Todorovic, M., Tanasijevic, L., Pereira, L.S., Pizzigalli, C. and Lionello, P. (2015) 'Climate change and Mediterranean agriculture: Impacts on winter wheat and tomato crop evapotranspiration, irrigation requirements and yield', Agricultural Water Management, 147, pp. 103–115. Available at: https://doi.org/10.1016/j.agwat.2014.05.008.
84. Sadok, W., Lopez, J.R. and Smith, K.P. (2021) 'Transpiration increases under high-temperature stress: Potential mechanisms, trade-offs and prospects for crop resilience in a warming world', Plant, Cell & Environment, 44(7), pp. 2102–2116. Available at: https://doi.org/10.1111/pce.13970.

85. Safeeq, M., Grant, G.E., Lewis, S.L. and Tague, Christina.L. (2013) 'Coupling snowpack and groundwater dynamics to interpret historical streamflow trends in the western United States', Hydrological Processes, 27(5), pp. 655–668. Available at: https://doi.org/10.1002/hyp.9628.
86. Sanden, B. (2010). Scientific irrigation scheduling in permanent crops: process, planning, programs & pressure bomb. Kern Irrigation Workshop. Kern Soil & Water Newsletter. 8 April 2010.
87. Scarpare, F.V., Rajagopalan, K., Liu, M., Nelson, R.L., Stöckle, C.O., 2022. Evapotranspiration of Irrigated Crops under Warming and Elevated Atmospheric CO2: What Is the Direction of Change? Atmosphere 13, 163. https://doi.org/10.3390/atmos13020163
88. Şen, Z. (2021) 'Reservoirs for Water Supply Under Climate Change Impact—A Review', *Water Resources Management*, 35(11), pp. 3827–3843. Available at: https://doi.org/10.1007/s11269-021-02925-0.
89. Shukla, S., Safeeq, M., AghaKouchak, A., Guan, K. and Funk, C. (2015) 'Temperature impacts on the water year 2014 drought in California', Geophysical Research Letters, 42(11), pp. 4384–4393. Available at: https://doi.org/10.1002/2015GL063666.
90. Soderquist, Benjamin S.; Luce, Charles H. 2021. Climate change effects on hydrologic processes and water resources in the Sierra Nevada. In: Halofsky, Jessica E.; Peterson, David L.; Buluç, Lara Y.; Ko, Jason M., eds. Climate change vulnerability and adaptation for infrastructure and recreation in the Sierra Nevada. Gen. Tech. Rep. PSW-GTR-272. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 29-47. Chapter 3.
91. Stewart, I.T., Cayan, D.R., Dettinger, M.D., 2005. Changes toward Earlier Streamflow Timing across Western North America. Journal of Climate 18, 1136–1155. https://doi.org/10.1175/JCLI3321.1
92. Stöckle, C.O., Nelson, R.L., Higgins, S., Brunner, J., Grove, G., Boydston, R., Whiting, M., Kruger, C., 2010. Assessment of climate change impact on Eastern Washington agriculture. Climatic Change 102, 77–102. https://doi.org/10.1007/s10584-010-9851-4
93. Summers, C.G., Putnam, D.H. and University of California (System). (2008) Irrigated alfalfa management for Mediterranean and desert zones. Oakland, Calif.: University of California (University of California Agriculture and Natural Resources publication, 3512).
94. Sun, F., Berg, N., Hall, A., Schwartz, M. and Walton, D. (2019) 'Understanding End-of-Century Snowpack Changes Over California's Sierra Nevada', Geophysical Research Letters, 46(2), pp. 933–943. Available at: https://doi.org/10.1029/2018GL080362.
95. Swain, D.L., Langenbrunner, B., Neelin, J.D. and Hall, A. (2018) 'Increasing precipitation volatility in twenty-first-century California', Nature Climate Change, 8(5), pp. 427–433. Available at: https://doi.org/10.1038/s41558-018-0140-y.
96. United States Evnironmental Protection Agency. 2024. Harmful Algal Blooms (HABs) in Water Bodies: Climate Change and Freshwater Harmful Algal Blooms. Available at: https://www.epa.gov/habs/climate-change-and-freshwater-harmful-algal-blooms
97. Williams, L.E., Ayars, J.E., 2005. Grapevine water use and the crop coefficient are linear functions of the shaded area measured beneath the canopy.

Agricultural and Forest Meteorology 132, 201–211. https://doi.org/10.1016/j.agrformet.2005.07.010

98. Williams, L.E., Grimes, D.W. and Phene, C.J. (2010) 'The effects of applied water at various fractions of measured evapotranspiration on reproductive growth and water productivity of Thompson Seedless grapevines', Irrigation Science, 28(3), pp. 233–243. Available at: https://doi.org/10.1007/s00271-009-0173-0.
99. Wilson, T.S., Sleeter, B.M., Cameron, D.R., 2016. Future land-use related water demand in California. Environ. Res. Lett. 11, 054018. https://doi.org/10.1088/1748-9326/11/5/054018
100. Wilson, T.S., Sleeter, B.M., Cameron, D.R., 2016. Future land-use related water demand in California. Environ. Res. Lett. 11, 054018. https://doi.org/10.1088/1748-9326/11/5/054018
101. Xue, J., Huo, Z., Kisekka, I., 2021. Assessing impacts of climate variability and changing cropping patterns on regional evapotranspiration, yield and water productivity in California's San Joaquin watershed. Agricultural Water Management 250, 106852. https://doi.org/10.1016/j.agwat.2021.106852
102. Yourek, M., M. Liu, F.V. Scarpare, K. Rajagopalan, K. Malek, J. Boll, M. Huang, M. Chen, and J.C. Adam. (2023) "Downscaling Global Land-Use/Cover Change Scenarios for Regional Analysis of Food, Energy, and Water Subsystems." Frontiers in Environmental Science 11: 86.

CHAPTER 4: EVALUATING WATER CONSERVATION UNDER ALTERNATE LAND USE AND CLIMATE CHANGE SCENARIOS IN SAN JOAQUIN VALLEY, CALIFORNIA

4.1. Abstract

This study evaluates water-saving strategies by repurposing agricultural land for alternative uses, including habitat restoration, groundwater recharge, and solar energy development. Water availability in California's San Joaquin Valley has become increasingly limited due to climatic variations and regulatory restrictions on groundwater use, leading to pressures on surface and subsurface water storages, infrastructure, and the economic viability of farming. Climate change is expected to exacerbate water scarcity and increase agricultural water demand under current practices. The Sustainable Groundwater Management Act (SGMA) of 2014 requires water managers and farm owners to develop strategies to reduce agricultural water demand and achieve sustainable groundwater levels. To achieve this, one of the suggested demand side strategies of taking irrigated land out of production can have significant environmental and financial implications. Instead of leaving the fallowed land idle, a more sustainable way is repurposing the land for alternate use. This will have multiple benefits, but a comprehensive understanding of the impact on water conservation under any alternate land use under climate change scenarios is vital for their implementation. This study evaluates water-saving strategies by repurposing agricultural land for alternative uses, including habitat restoration, groundwater recharge, and solar energy development. Using the VIC-CropSyst model, the research conducts a large-scale assessment of water saving in diverse agricultural region. The analysis of water demand reductions across different scenarios revealed varying levels of water savings among land use strategies, with consistent outcomes across climate change scenarios. Large-scale land fallowing under habitat restoration in reducing water demand, groundwater recharge potential emerged as the most effective strategy, while solar development showed moderate reductions. Among the evaluated crops, perennial crops, especially, almonds showed the highest reduction in water demand, while corn showed the least. This study emphasizes on the importance of adopting crop-specific and farm-centric water repurposing strategies for effective water conservation. These results, in consideration with advantages and challenge of each alternate land use, will be helpful for developing effective policies for water conservation through multi-benefit land repurposing.

4.2. Introduction

Agriculture in California is heavily dependent on irrigation due to Mediterranean climate. Despite ongoing advancements in irrigation water efficiency, the issue of water availability continues to be a significant concern due to the shifting from annual to perennial crops. The availability of water is getting increasingly constrained due to droughts and regulatory restrictions on groundwater usage in recent years. This has not only further strained the existing water storage and infrastructure, but also made farming costlier and less profitable (Medellin-Azuara *et. al*, 2022). In addition, climate change is anticipated to cause further reduction in timely water availability and increase in agricultural water demand under the business-as-usual scenario

(Hanak and Lund, 2012). The recent implementation of the Sustainable Groundwater Management Act (SGMA) in 2014 has mandated water managers and farm owners to explore strategies for reducing agricultural water demand and bring groundwater levels to a sustainable level. A key water conservation strategy can be fallowing the irrigated farmlands or repurposing them for alternative uses. However, since taking land out of production is a significant financial step that also involves a change of land use, stakeholders may require further understanding of its impact on water conservation under future climate change.

While the reduction in irrigated land will aid in decreasing groundwater overdraft in line with SGMA, it will also lead to both direct and indirect effects on land use conversion, water and energy in land use, soil and water pollution, natural habitats, farming, and disadvantaged communities (Fernandez-Bou *et al*., 2023). Land fallowing can also make the agricultural system resilient to climate change (Schoeneberger *et al*., 2017). Fallowing also provides environmental benefits, such as aiding in water conservation, promoting biodiversity, enabling carbon sequestration, preventing land degradation (Żarczyński *et al*., 2023), and managing floods (Bark, 2021). This practice can also help in restoration of soil fertility by nutrient recycling, improvement of soil physical properties, and increase in organic matter and microbial diversity, as well as disrupting pest and disease cycles (Schoeneberger *et al*., 2017; Żarczyński *et al*., 2023). However, it may also lead to economic and environmental costs, such as rising prices for consumers, job losses in the agricultural sector (Hanak, 2003; Howitt and Sunding, 2003), reduction in revenue (Dixon *et al*., 1993), air quality deterioration (Ayres, Kwon, and Collins, 2022), and potential soil degradation (Scudiero *et al*., 2016; Corwin, 2020). Widespread fallowing of cropland has been used to tackle droughts in California in 1991, 2012-2016, and 2020-2021 (DWR, 1992; Howitt and Sunding, 2003; Rosevelt *et al*., 2016; Ayres *et al*., 2022). The type of crop grown governs the value of cropland being considered for fallowing and economic losses associated with them (Howitt and Sunding, 2003). The recent drought pf 2020 Medellín-Azuara, 2022). For receiving desirable outcomes from land fallowing while managing the trade-offs, requires a coordinated and strategic planning. In conclusion, assessment of water saving benefits and trade-offs associated with cropland fallowing should be further explored in unison.

Considering land is a finite and multifunctional resource, it should be utilized optimally by making use of its unique soil characteristics, climate, topography, and potential benefits. Instead of leaving agricultural fields fallow, those lands can be repurposed for sustainable alternatives that reduce water demand, replenish groundwater supplies, and provide measurable benefits to the environment or the broader community (EDF, 2021). In the San Joaquin Valley (SJV), several studies have suggested converting previously irrigated land with low agricultural output and native species habitat corridors for restoration (Lortie *et al*., 2018; Butterfield *et al*., 2017; McComb *et al*., 2022) and solar energy generation (Butterfield *et al*., 2013; Pearce *et al*., 2016; Hoffacker *et al*., 2017). The possibility of using fallowed agricultural land for groundwater banking has been investigated using soil suitability indices (O'Geen *et al*., 2015). Other options include using fallowed land for planting un-irrigated or low irrigation crops (Peterson *et al*., 2022), grazing areas, recreation or parks (Quandt *et al*., 2023). While strategic land retirement has recently gained attention (Kelsey *et al*., 2018), particularly with the SGMA in its early stages and GSAs starting their journey towards sustainability, many alternative land use proposals focus on a single objective or either habitat restoration, groundwater recharge, or renewable energy. Since climate change and ecosystem degradation

impacts fragile natural habitat, particularly for endangered species, the strategic restoration of habitats can be widened by considering them in conjunction with other objectives. Multi-benefit land repurposing in fallowed agricultural lands offers a promising opportunity for achieving ecological, economic, and social benefits. These benefits will be relevant once water saving potential of alternate land use and crop type is identified. Moreover, economic compensation for alternative use of cropland promotes water saving, ecosystem services and safeguarding community health. However, their sustainable implementation faces challenges, including the need for more flexible subsidies, stable participation, improved incentives for farmers, the provision of off-farm jobs, underutilization of land, and the diversity in farmers' opportunity costs (Deng et al., 2021). These incentive programs are offered by municipal, state, and federal entities. The effectiveness of these programs can be measured by quantifying the water saving for the given land and crop types.

Evaluating the dynamics and variability of agricultural evapotranspiration offers data-driven support for more efficient land use and water planning across different scales (Wong *et al*., 2021). Measuring evapotranspiration varies widely in terms of methodology, reliability, resolution, accuracy and cost. There are various methods based on mass or energy balance, soil-water balance or direct field measurements (Allen *et al.,* 1998). Some of the widely used methods are pan evaporation, lysimeters, eddy covariance, remote sensing, and land surface models. Ground-based methods such as eddy covariance is among the accurate methods. However, due to its high cost, time consumption and location-specific application (Allen et al., 1998), it is not suitable for largescale water use assessments. In comparison, soil-water balance models considers various factors (climate, soil, crop), useful for climate change-related water resources planning, but are data-intensive, potential for error propagation, requires detailed input data (Kibria *et al*., 2021). Remote sensing and land surface model techniques are cost-effective, extensive spatial coverage, useful in large-scale application. Nonetheless, they may provide biased or underestimated results in absence of calibration and validation with ground data (Kibria *et al*., 2021). However, unlike and land surface models, remote sensing-based estimation of agriculture water use does not account for the crops type, characteristics, and growth stages (Allen *et al.*, 2007). Depending on the need of study and scalability, one method can be better suited than the other. Understanding the uncertainty in quantifying water consumption over large areas and diverse land use within irrigated regions will aid in planning water resources and regulating supply.

It is pertinent to mention that studies evaluating the long-term impacts of alternative land use on water conservation in the face of climate change are scarce in California. There is a need for more detailed research to develop an estimation method to account for water use from multiple land uses and crop types. Since, there are several methods to evaluate agriculture water demand, the advantages and shortcomings of these methods should be studied. This study first evaluates the uncertainties in ET estimation by process-based hydrologic model and data-driven remote sensing products. The objective of this paper is to evaluate the potential water saving from land repurposing strategies for alternative and multiple land uses such as habitat restoration in conjunction with groundwater recharge and solar energy development. The type of crop dictates the amount of water use, this study along with average saving in total water demand, also analyzed how much water is being saved by fallowing of major crops under different land fallowing and climate change scenarios. The goal is to develop an assessment plan that identifies long term water conservation under changing climate and cropland uses when taken for retirement to

maximize water saving, ecological benefits, socioeconomic advantages for stakeholders and communities at large.

4.3. Methods

4.3.1. Study area

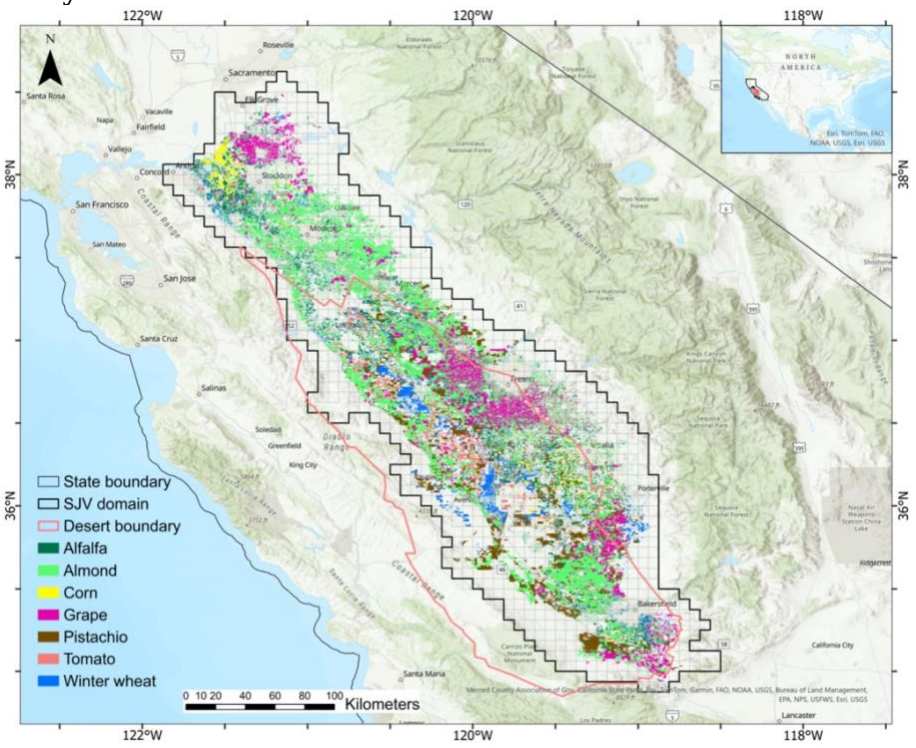


Figure 4.1: Map of study area showing SJV domain of study (black boundary) and delineated desert boundary in California (dark grey). Coloured regions in the SJV domain represents location of seven main crops.

The San Joaquin Valley (SJV) forms the southern part of California's Central Valley, extending from the Delta in the north to the Tehachapi Mountains in the south (Figure 4.1). It is a flat valley floor bordered by the Coast Ranges to the west and the Sierra Nevada mountains to the east. The flatness of the valley allows for large-scale mechanized farming and efficient irrigation systems. The region experiences a Mediterranean climate with hot, dry summers and mild, wet winters. Average annual precipitation is about 350 mm, mainly between November and March, with a decrease from north to south. The valley floor, covered in fertile alluvium deposited by rivers over millennia, features a gentle slope ideal for extensive farming.

Land use in the SJV is dominated by agriculture, with urban areas and natural vegetation like forests and wetlands making up a smaller portion. Around 5.7 million acres of irrigated agricultural areas produce a diverse range of crops, including fruits, nuts, vegetables, grains, and hay. The key crops in the region, selected for the study represent over 70% of irrigated crop area, including almonds (26%), grapes (10%), pistachios (10%), winter wheat (7%), alfalfa (7%), tomato (3%), and corn (2%) (USDA, 2020).

The SJV also includes the San Joaquin Desert, an ecosystem covering approximately 7,040 acres. The desert is characterized by low average precipitation (≤279 mm annually), arid soils, and extreme temperatures, making it suitable for specific flora and fauna. Climate conditions, including precipitation amount and

timing, soil moisture, drought, and air temperature, support extensive alkali sink scrub, saltbush shrublands, ephedra scrublands, grasslands, and desert ecosystems. The region has several unique and endangered species, such as the San Joaquin kit fox (Vulpes macrotis mutica), the blunt-nosed leopard lizard (Gambelia sila), and the giant kangaroo rat (Dipodomys ingens).

4.3.2. VIC-CropSyst model

This research utilized the coupled hydrology-crop model VIC-CropSyst to assess agricultural water demand across different crop categories. The VIC model, developed by Liang *et al*. in 1994, is a large-scale, process-based model that focuses on water and energy balances. It has been calibrated and applied in numerous studies in the Sierra Nevada region of California, including the current study. The CropSyst model, on the other hand, simulates the growth and development of individual crops based on their characteristics, irrigation, and planting dates to estimate daily evapotranspiration and biomass. By combining these two models, the integrated VIC-CropSyst model generates simulations of soil water balance, crop growth stages, water usage, and yield at a 1/16th degree grid scale (~6 km x 6 km). Phenological stages in this integrated model are determined by accumulated daily heat units in growing degree days, using a linear thermal response curve model, and chilling hours are calculated with the Utah Chilling Unit Model. This approach has been successfully used to study the effects of climate change on agriculture in various regions, including California, Washington, and the Columbia River basin.

Model calibration and validation involved identifying sensitive parameters for the VIC-CropSyst model based on previous studies defining annual growth stages for each crop, adjusting heat growing degree-day values, setting planting and harvesting dates for annual crops, determining phenological stages for crops like alfalfa and tree crops, specifying parameters for crop evapotranspiration (ETc). These parameters include crop coefficient, canopy coverage, leaf water potential, and root depth, and updating yield-related parameter values like dry yield or maximum fruit load values. Model calibration and validation involved several steps. First, sensitive parameters for the VIC-CropSyst model were identified based on previous studies. Secondly, annual growth stages for each crop were defined, and heat growing degree-day values were adjusted accordingly. Thirdly, planting and harvesting dates for annual crops were set, and phenological stages for crops like alfalfa and tree crops were determined. Fourthly, parameters for crop evapotranspiration (ETc) were specified, including crop coefficient, canopy coverage, leaf water potential, and root depth. Finally, yield-related parameter values, such as dry yield and maximum fruit load were updated.

4.3.3. Input data

The VIC-CropSyst model incorporates various input data, such as climate, land cover, atmospheric CO2 levels, soil characteristics, crop/vegetation phenology, physiology, and management details. For future climate projections, downscaled climate data from the Multivariate Adaptive Constructed Analogs (MACA) were employed, derived from four Global Circulation Models (GCMs) of the Coupled Model Intercomparison Project 5 (CMIP5). These GCMs encompass a spectrum of climate scenarios: HadGEM2-ES365 (warm/dry), CNRM-CM5 (cool/wet), CanESM2 (average), and MIROC5 (representing variability across all 10 CMIP5 GCMs recommended in California's Fourth Climate Change Assessment). The model maintains a constant atmospheric CO2 concentration of 360 parts per million (ppm). Soil input data were based on STATSGO2 data modified to fit the model's resolution for textural

characteristics, distribution, and hydrology. Initially, soil parameters were calibrated based on Maurer *et al*. (2002) and later updated using the latest climate averages, with the number of soil layers increasing from 3 to 17. Land cover information within the San Joaquin Valley (SJV) boundary was obtained from the USDA-NASS Crop Data Layer at a 30-meter spatial resolution. Fractional land cover for natural vegetation and crop classes was computed for each grid cell, with grids having a fractional area cover of 1% or more of selected crops chosen for simulation. Monthly Leaf Area Index (LAI) values for natural vegetation and crops (excluding the chosen 7 crops) were input as fixed values from Bohn and Vivoni (2019) in the vegetation file. Most input and calibration parameters, including approximate phenological stage dates, crop evapotranspiration (ETc), and crop yield information, were gathered from field trials in California, production manuals, published research, reports, and expert consultations.

The scenario raster layers and shapefiles for the fallowing, habitat corridors, groundwater and solar conflicting were collected from The Nature Conservancy (Butterfield, 2017). Spatial CIMIS reference ET data from multiple remote sensing and gridded products were downloaded from DWR website (DWR, 2022). Soil and Agricultural Groundwater Banking Index (SAGBI) data is also available for download from the California Soil Resource Lab at the University of California-Davis and University of California-Division of Agriculture and Natural Resources (O'Green 2015).

4.3.4. Model uncertainty analysis

The ETc output from the VIC-CropSyst model was compared with a gridded reference ET (ETo) derived ETc and two remotely sensed derived actual ET products. First product was California Irrigation Management Information System gridded product, Spatial CIMIS (hereafter "CIMIS"), which combines remotely sensed satellite data with traditional CIMIS station data to produce maps of daily ETo on a 2-km grid (DWR, 2022). Like VIC-CropSyst model, CIMIS uses Penman-Monteith equation to calculate ETo. ETc from Spatial CIMIS ETo for each crop in the grid was calculated by multiplying ETo with average crop coefficient (Allen *et al*. 1998, Sanden, 2010). The grid-level average ETc for the model and CIMIS was calculated by taking area weighted average of ETc for crops falling in those grids.
The second product was actual ET from OpenET[1] SSEBop (version 0.2.6, (hereafter "OpenET"),) and the third product was from USGS available VIIRS[2]. (for simplification actual ET is also referred as ETc for these products). Both OpenET and VIIRS use the Simplified Surface Energy Balance (SSEBop) model to calculate ET using remote sensing data. The SSEBop model is a thermal-oriented streamlined surface energy model to calculate actual evapotranspiration (ET) using the principles of satellite psychrometry (Senay *et al*., 2007; 2018). ETa raster dataset for OpenET and USGS VIIRS ET were initially processed in Google Earth Engine to sum

[1] The OpenET SSEBop implementation uses land surface temperature (Ts) from Landsat (Collection 2 Level-2 Science Products) with key model parameters (cold reference, Tc, and surface psychrometric constant, 1/dT) derived from a combination of climatological average (1980-2017) daily maximum air temperature (Ta, 1-km) from Daymet, and net radiation data from ERA-5

[2] The dataset's creation involves the integration of VIIRS-based land surface temperature, maximum air temperature from WorldClim, and reference ET obtained from gridded weather datasets such as TerraClimate by Abatzoglou et al. (2018) for global coverage.

seasonal water-year ETa. All datasets were downscaled to match the CDL layer spatial extent and resolution of 30 x 30 m. Then, average ETc calculations were performed for each layer. Summary statistics, including mean, standard deviation, and interquartile range, were then calculated for each product. Independent sample t-tests were conducted between the model average and each of the other three ET products. The baseline scenario consisted of base acreage (USDA, 2020) under seven selected crops.

4.3.5. Water demand in alternate land use and climate change scenarios

The baseline scenario consisted of base acreage (USDA, 2020) under seven selected crops. Potential land repurposing scenarios were identified based on Butterfield *et al.* (2017). Habitat corridors for five endangered desert species has been identified within the SJV's desert landscape by Stewart *et al*. (2019). These areas could potentially provide the scope for habitat restoration and strategic fallowing of irrigated lands in conjunction with other criteria. First, among the suitable sites for one or more species, the agricultural areas that were fallowed once or more during the 2011-2016 drought (Melton *et al*. 2015). These fallowed land parcels during the drought are supposedly the more likely candidates for permanent land retirement (Butterfield *et al*., 2017). Second, the suitable habitat areas that were not fallowed during the drought could be considered for future fallowing for habitat restoration. Third, suitable habitat sites with good, very good and excellent groundwater recharge potential (O'Geen *et al*., 2015). These zones have been identified using Soil and Agricultural Groundwater Banking Index (SAGBI) which determines suitability for groundwater recharge on agricultural land. The index scores are based on five factors crucial for successful agricultural groundwater banking, including deep percolation, the duration of residence time in the root zone, the land's topography, any chemical constraints, and the condition of the soil surface. Fourth, habitat sites coinciding with least conflict areas for solar energy development (Pearce *et al*., 2016). These areas include priority, least and potential areas of solar development identified in consensus between environmental, agricultural, and solar energy industry groups. The spatial maps developed for baseline and four alternate land use for habitat restoration, groundwater recharge potential, and solar development are defined below (Appendix C Figure S2):

Scenario 1: Baseline (base area with current acreage of crops for water demand)
Scenario 2: HBF (suitable habitat areas with fallowing history),
Scenario 3: HBNF (suitable habitat areas with no fallowing history),
Scenario 4: GWRP (suitable habitat sites with good, very good and excellent groundwater recharge potential),
Scenario 5: SDP (suitable habitat sites having least conflict solar energy development potential).

The average volume of water demand for each raster layer was calculated for the 30 m x 30 m grids and then averaged for the base area of all scenarios, which were kept same as that of baseline (no fallowing). The VIC-CropSyst modeled ETc for seven select crops from four GCM (CanESM2, CNRM-CM5, HadGEM2-ES365, MIROC5) was used to average yearly total seasonal water use for the seven crops, and their area weighted average was used to calculate the average water demand under each scenario. The ensemble mean ETc and crop acreage data were used to quantify the volume water demand under five alternate land use and two climate scenarios (RCP 4.5 and RCP 8.5). Climate change analysis for crops was expanded to include the gradual changes in the 21st century by dividing into three 30-year intervals

(2010-2039 as early, 2040-2069 as mid, and 2070-2099 as late). Finally, demand reduction potential of the crops was calculated as the per unit area reduction contributed by each crop by dividing the total volume reduction by each crop in each scenario by the total area under the baseline scenario.

4.5. Results

4.5.1. Model uncertainty

The average seasonal ETc values estimated for the study domain from four sources showed distinction from each other. The VIC-CropSyst model's mean ETc (1160 mm/year) was comparable with the mean value of CIMIS (1170 mm/year) but was much higher than those of VIIRS (870 mm/year) and OpenET (760 mm/year). The dispersion of data points were seen to be highest in OpenET values and lowest in the CIMIS (Figure 4.2). The spatial variation (represented by standard deviation) was highest for OpenET (242 mm), followed by VIC-CropSyst (171 mm), VIIRS (182 mm) and lowest by CIMIS (59 mm). The values were found to be slightly negatively skewed around the median for VIC-CropSyst, OpenET and VIIRS, while for CIMIS the distribution was symmetrical.

The paired t-test results indicate statistically significant differences between the ETc from VIC-CropSyst model and the other three products. The t-value was lowest for CIMIS (34), higher for OpenET (194), but highest for VIIRS (870). The p-value was less than 0.01 in all instances, so, the difference between the groups is unlikely to be due to randomness. The degree of freedom was constant in all instances.

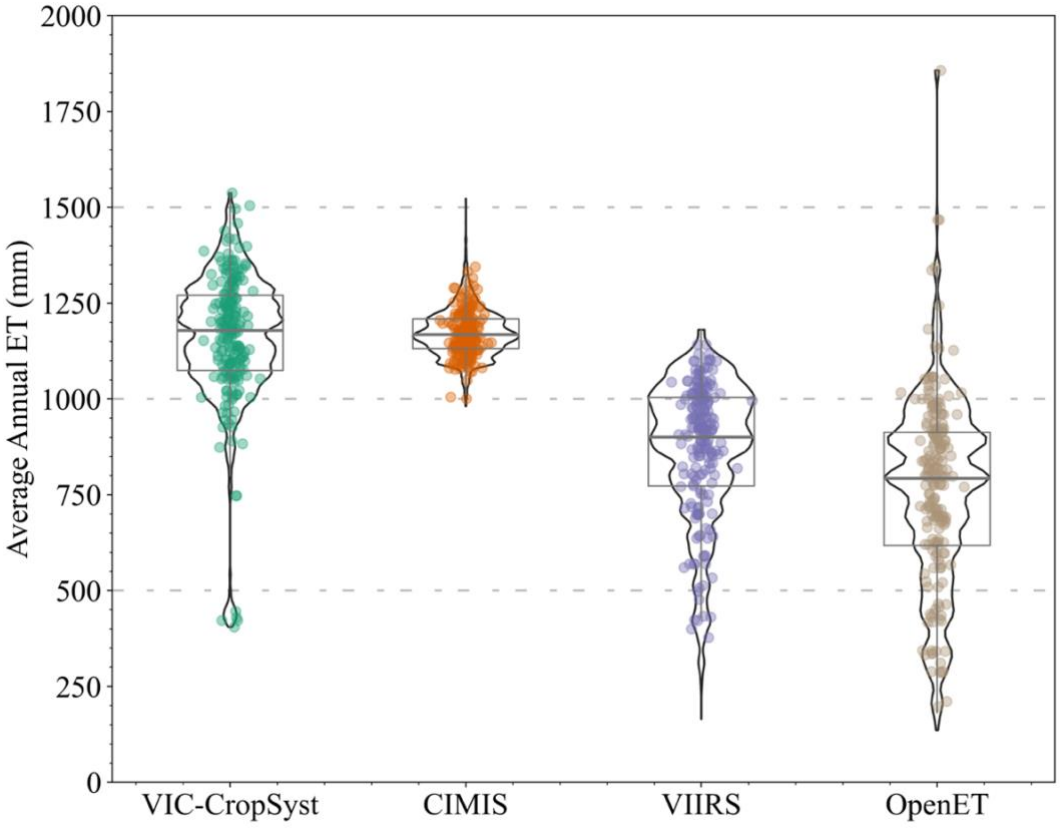


Figure 4.2: Estimation of ETc from VIC-CropSyst model, Spatial CIMIS, VIIRS and OpenET products. The box and violin plot represents median, interquartile range and variation in space.

4.5.2. Water demand in alternate land use and climate change scenarios

The analysis performed on average ETc, area, and water demand reductions under various scenarios revealed varying water saving among land use scenarios, but similar results among climate change scenarios (Figure 4.3 and Table 4.1). The reduction in acreage under land use scenarios drove the change in reduction in volume of water demand. The total baseline area of 3,294 thousand acres (TAc) was reduced by 11% in the HBF, 34% in HBNF, 27% in GWRP and 7% in SDP scenarios. Depending on the land use scenario, the baseline water demand of 13,750 TAF in RCP 4.5 can reduce by 3,090 TAF (22%) under HBNF to lowest of 880 TAF (6%) under SDP scenario. Similarly, in RCP 8.5, the base demand of 13,690 TAF can be reduced by 3,080 TAF (23%) under HBNF to lowest of 880 TAF (6%). The intermediate reduction was estimated under GWRP (20%) and HBF (10%) under both climate scenarios. Comparing the results between RCP 4.5 and RCP 8.5 showed slightly higher reductions in the RCP 8.5 scenario across crops and land use scenarios. Spatial variation in average demand depth for each scenario revealed higher values ranging from 105 to 130 mm/year among both climate scenarios (Appendix Table S1). However, because the values were found to be close for both climate scenarios the further analyses are presented and discussed for the extreme warming scenario of RCP 8.5 for simplicity. Spatial variation in average demand depth for each scenario revealed higher values ranging from 0.34 to 0.42 feet/year (105 to 130 mm/year).

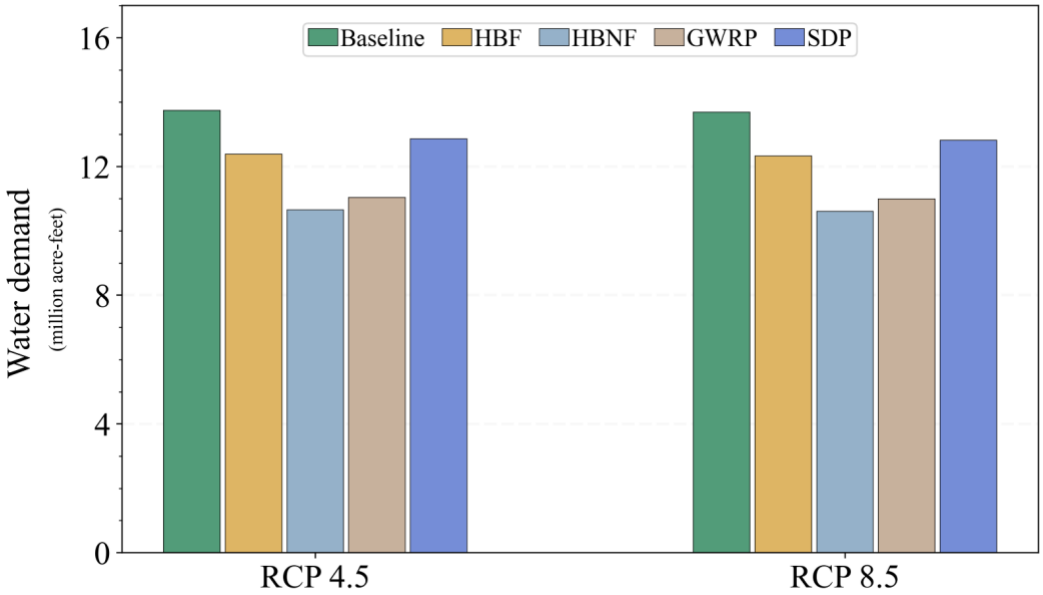


Figure 4.3: Average water demand under 5 land use and 2 climate change scenarios. The water demand volume is calculated by taking ensemble mean ETc simulated by VIC-CropSyst using four GCMs (CanESM2, CNRM-CM5, HadGEM2-ES365, MIROC5) and weighted averaged them spatially for area coverage. HBF: suitable habitat areas with fallowing history, HBNF: suitable habitat areas with no fallowing history, GWRP: suitable habitat sites with good to excellent groundwater recharge potential, and SDP: suitable habitat sites with solar development potential.

4.5.3. Crop-wise water demand reduction

Crop-specific water demand reduction determined by crop ETc and acreage yielded highest reduction by perennial crops, especially almond (Figure 4.4 and Table 4.1). The baseline water demand was highest for almond at 5,750 TAF (under acreage of 1,276 TAc) and lowest was for corn at 210 TAF (acreage of 106 TAc), reflecting the range of initial water requirements for these crops. Almond's highest reduction was

under HBNF by 1,270 TAF (i.e., 22% of base demand by excluding of 420 TAc acreage) and lowest was in SDP 230 TAF (reduced acreage (52 TAc) Among land use scenarios, almond had the maximum demand reductions in all alternate land use scenarios, while corn had the least reductions. This was followed by pistachio, grapes, alfalfa, wheat, and tomato under HBF, HBNF and GWRP scenarios. In the HBF scenario, the second highest demand reduction was for pistachios at 16% from its baseline value. A significant reduction of 24 to 25% was estimated for corn, alfalfa, and tomato from their baseline values in the HBNF scenario. In the GWRP scenario, reductions were moderately high for all crops, with 12% reductions for wheat (highest among annual crops) to more than 20% for almond, pistachio, and grape crops. Under SDP, the reductions was among the least for almost all crops, except a notable reduction for tomato at 17%.

The demand reduction across early, mid, and late periods of 21st century under climate change scenarios showed gradual decreasing or increasing pattern among annual and perennial crops (Appendix C, Figure S1). This was influenced by the changing growth cycles and ETc of the crops in the future climate scenarios. In general, annual crops had decreasing trends from early to late periods, while the perennial crops had slightly increasing trends (except almonds, which has a slight decreasing trend). Wheat reductions were found to decrease at faster rate across periods than corn and tomato crops. While for perennial crops, the rate of change was not significant among all crops and scenarios.

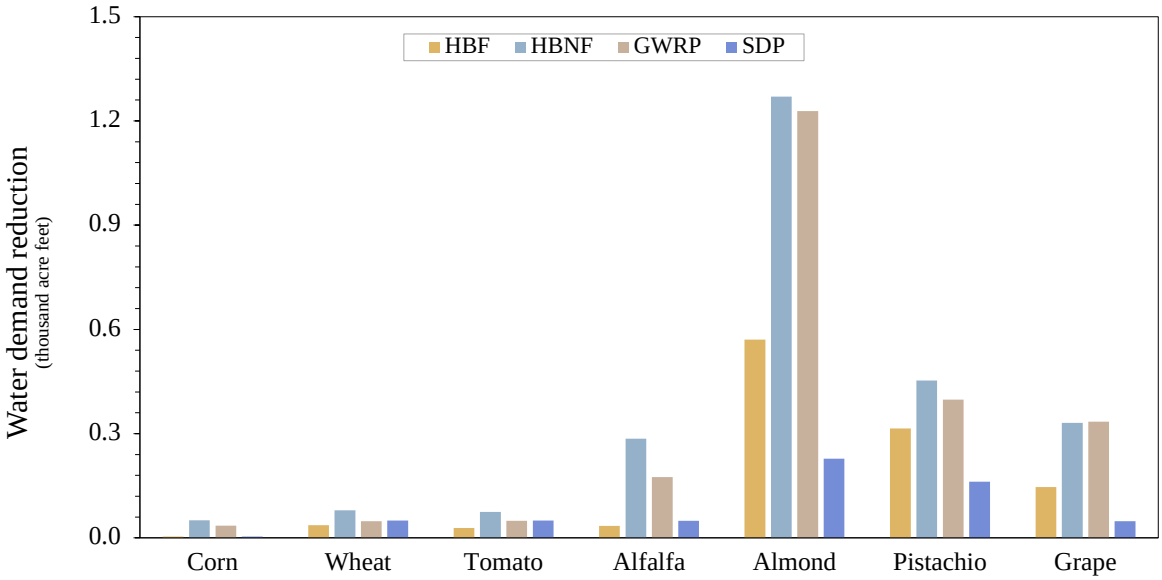


Figure 4.4: Water demand reduction from the baseline water use by each crop under 4 land use scenarios in RCP 8.5. The water demand volume by each crop is calculated by taking ensemble mean ETc simulated by VIC-CropSyst using four GCMs (CanESM2, CNRM-CM5, HadGEM2-ES365, MIROC5) and averaging them spatially for their area coverage. HBF: suitable habitat areas with fallowing history, HBNF: suitable habitat areas with no fallowing history, GWRP: habitat sites with good to excellent groundwater recharge potential, and SDP: habitat sites with solar development potential.

The demand reduction potential per unit area was higher for perennial tree crops (Figure 4.5). Under HBF, the demand reduction potentials were relatively modest across all crops. For this scenario, the tree crops demonstrated higher potential than alfalfa and annual crops. Additionally, almond showed the highest reduction at 0.17 acre-feet per acre (ac-ft/ac), while corn and wheat exhibited negligible

reductions. Under HBNF and GWRP, the perennial tree crops and alfalfa exhibited higher values, while moderate reductions by annual crops. A similar notable potential was observed for almond these two scenarios. All crops, including perennial crops, showed the lowest saving potential under SDP. Among other scenarios, alfalfa had the higher saving under HBNF and GWRP.

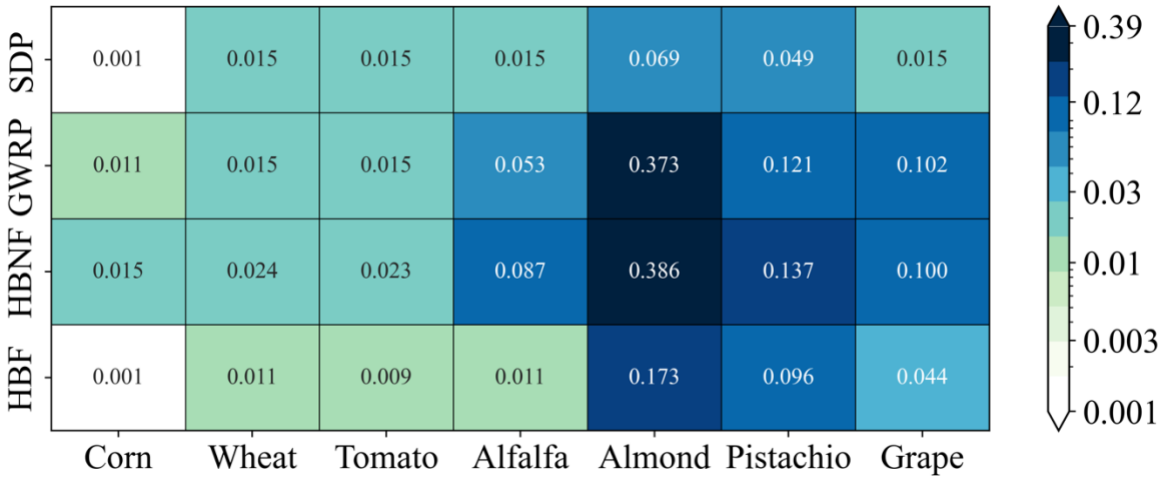


Figure 4.5: Water demand reduction (in acre-feet per acre) by each crop under four land use scenarios in RCP8.5. HBF: suitable habitat areas with fallowing history, HBNF: suitable habitat areas with no fallowing history, GWRP: habitat sites with good to excellent groundwater recharge potential, and SDP: habitat sites with solar development potential.

Table 4.1: Average ET, area and volumetric demand under five land use scenarios and two climate change scenarios. Volumetric demand is calculated by multiplying ETc with area under each land use.

Parameters		Average	Corn	Wheat	Tomato	Alfalfa	Almond	Pistachio	Grape
RCP4.5									
ETc (feet)	Baseline	4	2	1	2	4	5	4	3
	HBF	4	2	1	2	3	4	3	3
	HBNF	3	1	1	1	2	3	3	2
	GWRP	3	2	1	2	3	3	3	2
	SDP	4	2	1	2	3	4	4	3
Reduced area (thousand acres)	Baseline*	3,294	106	321	157	326	1,276	496	471
	HBF	370	2	31	17	10	143	96	51
	HBNF	1,127	40	81	73	143	420	166	155
	GWRP	880	22	43	32	60	391	131	158
	SDP	227	2	45	33	14	53	44	16
Reduced demand (thousand acre-feet)	Baseline*	13,747	216	441	308	1,144	5,821	2,031	1,499
	HBF	1,367	4	39	30	34	578	316	146
	HBNF	3,090	52	84	77	281	1,285	454	329
	GWRP	2,707	36	51	51	173	1,243	398	332
	SDP	881	4	53	52	48	231	162	48
RCP 8.5									
ETc (feet)	Baseline	4	2	1	2	4	5	4	3
	HBF	4	2	1	2	3	4	3	3
	HBNF	3	1	1	1	2	3	3	2
	GWRP	3	2	1	2	3	3	3	2
	SDP	4	2	1	2	3	4	4	3
Reduced area (thousand acres)	Baseline*	3,294	106	321	157	326	1,276	496	471
	HBF	370	2	31	17	10	143	96	51
	GWRP	1,127	40	81	73	143	420	166	155
	HBNF	880	22	43	32	60	391	131	158
	SDP	227	2	45	33	14	53	44	16
	Baseline*	13,693	211	416	299	1,158	5,748	2,027	1,505

Reduced demand (thousand acre-feet)	HBF	1,363	4	37	29	35	571	315	146
	GWRP	3,083	51	79	75	285	1,270	453	331
	HBNF	2,701	35	48	50	175	1,229	398	335
	SDP	878	4	50	50	49	228	162	48

* Denotes absolute values for baseline for area and demand.

4.6. Discussion

4.6.1. Uncertainty in crop ET estimation

The comparison of four different methods used for estimating ETc in agricultural landscapes led to a better understanding of their methodologies, advantages, weaknesses, and differences in results. The differences in ETc estimates are primarily due to the input data, modeling technique and spatial resolutions of the models. CIMIS calculates ETo from ground-based weather stations spread all over California and extrapolate them using remote sensing products. By combing ETo with average select crops crop coefficient values, the mean ETc estimation is be expected to be most accurate of all four methods. The higher spatial resolution of CIMIS compared to VIC-CropSyst model added advantage to accuracy. The methods is also found to be computationally efficient. However, the lowest spatial variability in the output implies that the estimates may does reflect different soil types and crops' irrigation patterns, especially in heterogeneous landscapes. The average estimation of ETc by VIC-CropSyst model was in close agreement with the CIMIS results. Despite its coarse resolution, the VIC-CropSyst model demonstrated higher spatial variability, indicating its capability to represent the diversity in topography and crop types. This accuracy is attributed to its calibration and validation for each crop based on local soil and climatic conditions. This model and CIMIS use the Penman-Monteith equation to estimate reference ET (ETo) using climate data with crop coefficient value to calculate daily ETc, which tends to capture crops growth stages. Since they do not account for water stress, they are likely to overestimate the results (Wong *et al.*, 2021). There are also physical constraints, parameters, and structural errors due to measurement of surface resistance and energy imbalance (Hu *et al.*, 2021). Additionally, the complexity of the land-surface models requires extensive input data and significant computational resources (Wanniarachchi and Sarukkalige, 2022), which can limit its widespread application.

OpenET and VIIRS products, using the SSEBop model, provided actual ET based on surface energy balance, but were shown to be lower than the average ETc for the region (DWR, 2018). This could be because they combine multiple products (for climate and land use), which can lead to underestimation due to the absence of irrigation or precipitation data (Kibria *et al.*, 2021). Even with underestimated mean, their spatial variability was similar to the one demonstrated by the model. The spatial resolution and variability also affect the quality of results, with higher resolutions (1-km for OpenET and VIIRS) capturing finer details compared to the coarser 2-km and 6-km grids of CIMIS and VIC, respectively. The higher spatial resolution provides direct estimates of actual ET and relies on readily available remote sensing data. SSEBop is a simplified approach that omits some components of surface energy balance, which has been reported to perform well with low errors in the irrigated fruit and nut orchards in Central Valley (Knipper *et al.*, 2024; Volk *et al.*, 2024).

Data driven remotely sensed ET methods are consistent and cost-effective for large area applications but require calibration and validation for reliable results across different agricultural profiles (Allen et al., 2007; Hu *et al.*, 2021; Wanniarachchi and Sarukkalige, 2022). The accuracy of these products is also contingent on the quality

and frequency of the satellite data. The measurement by these methods are not contained by physical parameters, which along with being advantageous, is subjected to poor interpretability of results and relationships within data (He *et al*., 2021). The nature of this study requires measuring ETc across a large area with varying climates, soils, growth cycles, and irrigation practices to infer meaningful conclusions regarding distinct land use and crop types. Therefore, among other approaches, the VIC-CropSyst model's comprehensive approach, low error rates, and ability to account for spatial variability have proven to be valuable for large-scale water resource assessments in heterogeneous agricultural regions.

4.6.2. Water saving by land use scenarios

The analysis of reduction of water demand through agriculture land repurposing strategies revealed significant differences in their efficiency of potential water conservation in future climate scenarios. In evaluating these strategies, groundwater recharge emerged as a particularly impactful approach due to its multiple benefits of reducing water demand, enhancing water availability along with environmental advantages. Financial incentives and coordinated planning can mitigate its challenges, making it a viable long-term solution for water management in the SJV. However, depending on land suitability and need, a multifaceted approach that integrates suitable habitat with solar energy development can leverage the strengths of each strategy. This combination promotes a sustainable solution by maximizing collective benefits across economic, environmental, and social dimensions.

The results suggested that by implementing fallowing on habitat suitable sites and groundwater recharge zones could be most effective in reducing water demand. Large land fallowing under these scenarios consistently showed significant reductions in demand for all crops under both RCP4.5 and RCP8.5 scenarios. Solar development sites demonstrated more moderate reductions due to lesser area coverage. The identification of over 150734 acres (610 km², Stewart *et al*., 2019) of fallowed or retired agricultural land with high habitat suitability potential highlights the significant opportunities for desert ecosystem restoration in the SJV. Alongside, multifunctional agricultural landscapes with environmentally friendly practices can enhance the ecological and environmental value of the land while maintaining comparable outputs (Rega *et al*., 2019), making it vital to examine agricultural production and land-use changes in relation to biodiversity and water conservation. Land-use, land characteristics and proximity to natural resources govern the environmental outcomes and existence of species in the region. Thus, by studying the systematic association between the occurrence of endangered species and cropland changes at regional scale can aid species conservation and incentivization policies (ERS-USDA, 2006).

Integrating groundwater recharge with suitable habitat lands can provide dual benefits, supporting both water sustainability and biodiversity conservation (Stewart *et al*., 2019). Promoting results from indices that identify potential groundwater zones, such as SAGBI, can be a cost-effective way of helping land and water managers assess recharge viability in their own areas (Bruce *et al*., 2023). Artificial groundwater recharge is a viable and economically beneficial strategy for ensuring sustained water availability, while mitigating land subsidence (Botzan *et al*., 1999; Faunt *et al*., 2016; Ulibarri *et al*., 2021). Implementing groundwater recharge infrastructure is costly and faces challenges such as land use conflicts, regulatory complexities, and variable effectiveness depending on soil and climate conditions (Botzan et al., 1999; Bachand et al., 2016; Dahlke et al., 2018). An effective

implementation would require evaluating the trade-offs of existing crops on the land (as discussed in detail in the subsequent section), assessing the underlying groundwater quality, and considering the needs of nearby communities. In California, groundwater quality information has been made publicly accessible through the Groundwater Ambient Monitoring and Assessment (GAMA) Program, which centralizes and displays water quality data from various sources on an interactive map (State Water Board, 2023). Another is the DWR's DAC Mapping Tool (DWR, n.d.) is useful for locating disadvantaged communities (DACs) across the state. Overlaying the spatial map of suitable groundwater recharge sites with groundwater quality and disadvantaged community data will help identify more suitable areas for recharge.

The overlap between proposed habitat sites and solar energy development areas is minimal, contributing to water savings in this case. The development of utility-scale solar energy is an attractive option for landowners, particularly those with or without water rights, as it provides an opportunity to keep lands that exit irrigated production economically productive (Butterfield *et al*., 2017). Agrivoltaics, which combines solar power generation with vegetation, has shown potential benefits in enhancing resilience to climate change while providing additional environmental and economic benefits compared to areas without vegetation (Choi *et al*., 2023). By considering opportunities, limitations, and trade-offs in site selection, solar energy development can align better with energy production, food security, and conservation goals (Hernandez *et al*., 2015).

Changes in water use from individual scenario are direct effects of land repurposing, but there are also indirect effects on agricultural inputs and supply, the regional economy, the labor market, and related industries (Sunding and Ronald-Holst, 2020; Fernandez-Bou *et al*., 2023). The execution of water conservation measures should adopt comprehensive methods that account for both the hydrological and financial dimensions (Eslamifar *et al*., 2024). To get a holistic understanding of each land conversion strategy, literature review was conducted to synthesize and compare their key aspects (Table 4.2).

Table 4.2: Overview of land repurposing strategy uses, benefits, drawbacks, challenges, potential solutions, beneficiaries, case studies and references.

Strategy	**Habitat suitability**	**Groundwater recharge**	**Solar energy development**
Use	Habitat restoration	Increase water availability	Source of renewable energy
Benefits	Enhance biodiversity, support endangered species, improves landscape connectivity, supports wildlife conservation	Enhances water quality, mitigate drought, supports wetland ecosystems, reduces subsidence	Alternative income, dust mitigation, supports soil health, reduces agricultural risks
Drawbacks	Potential loss of agricultural revenue, initial costs	High infrastructure costs, land use conflicts	High initial costs, potential conflicts with agriculture
Challenges	Financial feasibility, habitat fragmentation, disease spread, introduction of invasive species	Regulatory complexities, variability in recharge effectiveness	Financial feasibility, regulatory challenges, habitat impact

Potential solutions	Agri-environmental programs, strategic planning, policies promoting multifunctional landscapes	Financial incentives, continued research and monitoring (using models and geoinformatics), coordinated planning, stakeholder engagement including farmers, policymakers and conservationists	Innovative financing models, policy reforms, agrivoltaics systems
Beneficiaries	Endangered species, ecosystem health	Farmers, water managers, ecosystems	Landowners, renewable energy sector, agriculture
References	Stewart et al., 2019; ERS-USDA, 2006; McComb et al., 2022; Bryant et al., 2020; Newman et al., 2017; Cuppari et al., 2024; Stewart et al., 2019; Lauer et al., 2023; McComb et al., 2022; Hernandez et al., 2015; Rega et al., 2019; Newman et al., 2017	Bruce et al., 2023; Botzan et al., 1999; Bachand et al., 2016; Bark, 2021; Bryant et al., 2020; Stewart et al., 2019; Ulibarri et al., 2021; Bachand et al., 2016; Hannah et al., 2020; Marwaha et al., 2021; Faunt et al., 2016; Bachand et al., 2016; Botzan et al., 1999; Ulibarri et al., 2021; Dahlke et al., 2018; Botzan et al., 1999; Quandt et al., 2023; Marwaha et al., 2021; Faunt et al., 2016; Bruce et al., 2023; Faunt et al., 2016; Dash et al., 2016; Deepa et al., 2016; Charbonneau and Kondolf, 1993	Butterfield et al., 2017; Stid et al., 2022; Butterfield et al., 2017 Choi et al., 2023; Hernandez et al., 2015; Choi et al., 2023; Hoffacker et al., 2017; Stewart et al., 2019; Hernandez et al., 2014; Stid et al., 2022; Hernandez et al., 2015; Cuppari et al., 2024; Owley and Morris, 2019; Butterfield et al., 2013; Stid et al., 2022

Among the three land repurposing strategies for water conservation in the SJV, each approach has its own distinct advantages and faces specific challenges. Habitat restoration is notably beneficial for enhancing biodiversity, supporting endangered species. However, it involves high initial costs and potential loss of agricultural revenue. Groundwater recharge, will be effective in saving and augmenting water supply along with providing auxiliary benefits of mitigating drought impacts, improving water quality, and reducing land subsidence. This strategy will still necessitate infrastructure investment and encounters regulatory complexities. Solar energy development offers alternative income sources and supports renewable energy objectives, with added benefits such as dust mitigation and soil health improvement. Yet, it comes with financial feasibility concerns and potential conflicts with agricultural land use.

Promoting land use change policies will be more effective with including incentives and compensation for reducing groundwater consumption, achieving water savings, and offering ecosystem services. Fortunately, there are some success stories and upcoming programs that are promoting the incentivization. In some cases, farmers volunteer and receive compensation through fallowing agreements to save water or transfer it to other municipalities (Bark, 2021). Examples of these in California include the 1991 Drought Water Bank (DWR, 1992), Forbearance and Fallowing Program Agreement (PVID-MWD, 2004), Imperial Irrigation District

Fallowing Program (IID, 2014; IID, 2016), and Colorado River Water Transfer Agreement (SDCWA, 2020). In addition, the Conservation Reserve Program funded by the United States federal government is the largest land retirement program (Miao *et al*., 2016) that aims to minimize program costs, impacts on agricultural production and enhance ecological benefits by offering compensation for fallowing lands (Hellerstein, 2017). The Conservation Reserve Program selects parcels for enrolment based on factors like wildlife impacts and carbon sequestration (Miao *et al*., 2016). The Multibenefit Land Repurposing Program (MLRP), launched by the California Department of Conservation in 2022, aims to repurpose agricultural land to reduce groundwater reliance and provide multiple benefits. The program supports the development of less water-intensive agricultural practices and other land uses, which can create new job opportunities and stimulate local economies (Espinoza et al., 2023). Farmers who meet the income criteria are compensated to fallow their land either temporarily or permanently. The MLRP program is viewed as a sustainable and economical solution for California's agriculture industry (Department of Conservation, 2021). The LandFlex program is another initiative, offering financial incentives to farmers to fallow fields in critically overdrafted groundwater basins and near drinking water wells which are at risk of drying up (DWR, 2023). The funding for the LandFlex program is through DWR's Sustainable Groundwater Management (SGM) Grant Program. LandFlex, unlike other programs, requires applicants to also have an active groundwater pumping allocation plan and use a remote-sensed evapotranspiration (ET) accounting method or equivalent to measure the reduction in groundwater use on enrolled acres. These programs highlighted the need for accounting groundwater use reduction by land fallowing.

4.6.3. Crop specific considerations

The total reduction in water usage across all crops has varying effectiveness in water savings. Larger demand reductions were notable in perennial tree crops suggesting their higher area coverage and amount of water use will add to the effectiveness of water saving decision. Almonds exhibited the highest total reduction, followed by pistachios, and corn showing the least reduction. The increase or decrease in reducing demand by crops was consistent across early, mid, and late periods. The rate of change in magnitude change is related to the changes in their growth cycle due to warming. This implies that the long-term effectiveness of the water saving by crops will be affected by the changing climatic conditions. The rate of change was lesser in perennial crops suggests relatively consistent savings towards end of 21st century compared to annual crops.

The analysis of water use and reduction per unit area across different crops provided their efficiency under various land repurposing strategies. For the total crop area of 3,294 thousand acres under seven select crops, the base water usage per unit area serves as a benchmark for comparison across different reduction strategies. This metric is valuable for understanding the intensity of water savings on a per-unit-area basis, helping to identify which crops and strategies yield the highest savings per unit of land, and providing practical insights for optimizing water use. Land fallowing on suited habitat with groundwater recharge proves effective for water-intensive crops like almonds and pistachios. Crop selection among the land use strategies also plays a significant role in enhancing recharge and reducing groundwater use. Recharging groundwater by flooding alfalfa fields with highly permeable soils during winter has been proven effective, causing only minor crop and yield damages (Dahlke *et al*., 2018). Field experiments have shown that almost 90% of applied irrigation can

contribute to groundwater recharge. In the Central Valley, the conversion of 8,350 acres of agricultural land for solar installation is driven by the low opportunity cost associated with low-value field and hay crops (59%) (Stid *et al*., 2022).

The negative trade-offs and economic impacts of saving water by fallowing perennial croplands is also higher. Perennial crops like almonds and pistachios are among major contributors to the valley's economy. Fallowing these crops can lead to substantial economic losses, including reduced farm revenues and job losses. Reducing production has broader economic repercussions, especially affecting downstream industries such as transportation and food processing (Sunding and Roland-Holst, 2020). The fallowing of labor-intensive crops can affect rural and low-income communities, who rely on agricultural jobs leading to lower household spending, further exacerbating economic decline. Overall, while fallowing perennial crops can be a major step for sustainable water management, it requires careful planning to balance economic, environmental, and community needs.

The indirect impact of taking hay and field crops farmlands out of production will have indirect impact on the revenue and productivity of other related industry. Alfalfa, corn and wheat crops are used as feed for the dairy sector, which is the most profiting agriculture industry in California. Thought these indirect impacts are not accounted here, but this can be taken up for future study. Alternative to permanently fallowing some of these crops, a middle path can be making temporary land fallowing as a part of crop rotation. For example, wheat, which can be grown in the SJV with minimal irrigation, can serve as an alternative to land fallowing (Paterson *et al*., 2022). Similar innovative strategies should be explored to reduce the tradeoffs of idling land for conserving water.

4.7. Conclusion

Agriculture water saving through land fallowing, while an effective method for water conservation, can impose higher costs on farmers and cause market losses, leading to economic, social, and environmental distress. The potential benefits to biodiversity, ecological connectivity, water sustainability, and renewable energy development are substantial and should not be overlooked while planning alternate land use. The flexibility of land repurposing strategies, on the other hand, allows for their implementation alongside ongoing cropland production or fallowing for enhanced benefits. This research aimed to evaluate water conservation potential when land is strategically retired for alternative uses to maximizing ecological benefits while minimizing socioeconomic impacts. The findings suggest that land repurposing on suitable habitat sites with groundwater recharge can be viable solutions in that regard. Groundwater recharge strategy stands out as a particularly effective strategy due to its dual benefits of decreasing water demand and increasing water availability. Another strategy of repurposing for solar energy development with only moderate water saving presents significant economic and environmental benefits, yet it faces technical, economic, and policy challenges. By estimating reduction by key annual and perennial crops, helped to narrow down which crop can substantially impact water use reduction. Significant water demand reductions related to high-water-demand crops like almonds provides granularity that can inform better agricultural planning and decision making. This can lead to targeted and effective interventions, mitigating the overall water footprint and promoting agricultural conservation in water-scarce regions of the SJV. Expanding the analysis to include a broader range of

crops could provide a more comprehensive understanding of agricultural water use and reduction potential across the SJV.

Effective implementation these strategies requires considering tradeoffs between current and alternate use of land in terms of value of crops, derived impacts on other sectors, infrastructure costs, and incentives offered. There should be careful planning and robust policy support to ensure these strategies complement each other and contribute to comprehensive water conservation and resource management. The emphasis on adopting crop-specific, farm-centric water land repurposing strategies with incentive programs for conserving water is suggested. The detailed approach of quantifying water saving outlined in this study will help farmers and stakeholders to adapt water management practices to specific crops and climatic conditions, improving overall efficiency and sustainability of water use in agriculture. Alongside, multiple spheres will benefit from such studies including nature conservationists, energy sector, landowner, policy and incentive program regulators and community at large. Future research should investigate the long-term impacts of water reduction strategies, including economic and environmental benefits from the potential habitat restoration on non-fallowed and groundwater recharge augmenting lands. Additionally, research and policy development should aim to align solar energy projects with agricultural and environmental goals to create a balanced approach that supports economic growth, environmental protection, and food production. These outcomes can guide agricultural practices towards more efficient water management, ensuring the sustainability of water resources in the SJV amidst the challenges posed by regulatory and climate changes.

4.8. References

1. Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998) ‘Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56.’ FAO, Rome, 300, D05109
2. Ayres, A., Kwon, J., Collins, J. and Morales, J. (2022) ‘Land Transitions and Dust in the San Joaquin Valley’.
3. Bachand, P.A.M., Roy, S.B., Stern, N., Choperena, J., Cameron, D. and Horwath, W.R. (2016) ‘On-farm flood capture could reduce groundwater overdraft in Kings River Basin’, *California Agriculture*, 70(4), pp. 200–207. Available at: https://doi.org/10.3733/ca.2016a0018.
4. Bark, R.H. (2021) ‘Designing a Flood Storage Option on Agricultural Land: What Can Flood Risk Managers Learn from Drought Management?’, *Water*, 13(18), p. 2604. Available at: https://doi.org/10.3390/w13182604.
5. Bryant, B.P., Kelsey, T.R., Vogl, A.L., Wolny, S.A., MacEwan, D., Selmants, P.C., Biswas, T. and Butterfield, H.S. (2020) ‘Shaping Land Use Change and Ecosystem Restoration in a Water-Stressed Agricultural Landscape to Achieve Multiple Benefits’, *Frontiers in Sustainable Food Systems*, 4, p. 138. Available at: https://doi.org/10.3389/fsufs.2020.00138.
6. Botzan, T.M., Necula, A.I., Mariño, M.A. and Başağaoğlu, H. (1999) ‘Benefit-Cost Model for an Artificial Recharge Scenario in the San Joaquin Valley, California’, *Water Resources Management*, 13(3), pp. 189–203. Available at: https://doi.org/10.1023/A:1008025311732.
7. Bruce, M., Sherman, L., Bruno, E., Fisher, A.T. and Kiparsky, M. (2023) ‘Recharge net metering (ReNeM) is a novel, cost-effective management

strategy to incentivize groundwater recharge', *Nature Water*, 1(10), pp. 855–863. Available at: https://doi.org/10.1038/s44221-023-00141-1.

8. Butterfield Scott, H *et al*. "Identification of Potentially Suitable Habitat for Strategic Land Retirement and Restoration in the San Joaquin Desert." (2017): 1–25. Web. <https://www.scienceforconservation.org/assets/downloads/SLR-Habitat_-2017-lo.pdf>.
9. Butterfield, H.S., D. Cameron, E. Brand, M. Webb, E. Forsburg, M. Kramer, E. O'Donoghue, and L. Crane (2013). Western San Joaquin Valley least conflict solar energy assessment. The Nature Conservancy, CA. http://scienceforconservation.org/ downloads/WSJV_Solar_Assessment.
10. California Department of Water Resources (DWR). (1992). The 1991 DROUGHT WATER BANK
11. California Department of Water Resources (DWR). 2018. Cal-SIMETAW Unit Values. https://data.cnra.ca.gov/dataset/46c9d40b-fbb5-4ea0-9437-f84138d0b966/resource/dea8ef15-c3ed-4c18-a129-85a99f0a657f/download/calsimetawunitetdata_2018-08-02_publish.csv
12. California Department of Water Resources (DWR). (2022). Spatial CIMIS. Available at: https://catalog.data.gov/dataset/cimis-spatial-eto-maps-bb3e2
13. California Department of Water Resources (DWR). (2023) *LandFlex Grant Program Guidelines*. Available at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Work-With-Us/Grants-And-Loans/LandFlex/landflex_final_2023guidelines_13_January2023.pdf.

13. California Department of Water Resources (DWR). (2023) DAC Mapping Tool. Available at: https://gis.water.ca.gov/app/dacs/.
14. Charbonneau, R. and Kondolf, G.M. (1993) 'Land use change in California, USA: Nonpoint source water quality impacts', *Environmental Management*, 17(4), pp. 453–460. Available at: https://doi.org/10.1007/BF02394661.

14. Choi, C.S., Macknick, J., Li, Y., Bloom, D., McCall, J., Ravi, S., 2023. Environmental Co-Benefits of Maintaining Native Vegetation With Solar Photovoltaic Infrastructure. Earth's Future 11, e2023EF003542. https://doi.org/10.1029/2023EF003542
15. Corwin, D.L. (2021) 'Climate change impacts on soil salinity in agricultural areas', *European Journal of Soil Science*, 72(2), pp. 842–862. Available at: https://doi.org/10.1111/ejss.13010.

15. Cuppari, R.I., Fernandez-Bou, A.S., Characklis, G., Ramirez, M., Nocco, M.A., Abou-Najm, M., 2024. Drivers of agrivoltaic perception in California and North Carolina. Environ. Res.: Food Syst. https://doi.org/10.1088/2976-601X/ad5449
16. Dahlke, H.E., Brown, A.G., Orloff, S., Putnam, D. and O'Geen, T. (2018) 'Managed winter flooding of alfalfa recharges groundwater with minimal crop damage', *California Agriculture*, 72(1), pp. 1–11. Available at: https://doi.org/10.3733/ca.2018a0001.
17. Dash, Ch.J., Sarangi, A., Adhikary, P.P. and Singh, D.K. (2016) 'Soil water budgeting approach to quantify potential groundwater recharge from croplands and groundwater use in a semi-arid region', *Environmental Earth Sciences*, 75(10), p. 853. Available at: https://doi.org/10.1007/s12665-016-5620-7.
18. Deepa, S., Venkateswaran, S., Ayyandurai, R., Kannan, R. and Vijay Prabhu, M. (2016) 'Groundwater recharge potential zones mapping in upper Manimuktha Sub basin Vellar river Tamil Nadu India using GIS and remote

sensing techniques', *Modeling Earth Systems and Environment*, 2(3), p. 137. Available at: https://doi.org/10.1007/s40808-016-0192-9.
19. Deng, H., Guan, B., Wang, J., Zuo, A., Wang, Z. and Sun, T. (2021) 'Seasonal Land Fallowing Policy in Response to Groundwater Overdraft in the North China Plain', 14(2)
20. California Department of Conservation (2021) 'Multibenefit Land Repurposing Program-PROPOSED PROGRAM SUMMARY'.
20. Dixon, Lloyd S., N. Moore, and S. Schechter (), "California's 1991 Drought Water Bank," Rand Corporation, prepared for the California Department of Water Resources.
22. Environmental Defense Fund (EDF). *Advancing Strategic Land Repurposing and Groundwater Sustainability in California*. N.p., (2021). Web.
23. Eslamifar, G., Balali, H. and Fernald, A. (2024) 'Fallowing Strategy and Its Impact on Surface Water and Groundwater Withdrawal, and Agricultural Economics: A System Dynamics Approach in Southern New Mexico', *Water*, 16(1), p. 181. Available at: https://doi.org/10.3390/w16010181.
24. Espinoza, V., Bernacchi, L.A., Eriksson, M., Schiller, A., Hayden, A. and Viers, J.H. (2023) 'From fallow ground to common ground: Perspectives on future land uses in the San Joaquin valley under sustainable groundwater management', *Journal of Environmental Management*, 333, p. 117226. Available at: https://doi.org/10.1016/j.jenvman.2023.117226.
24. Faunt, C.C., Sneed, M., Traum, J. and Brandt, J.T. (2016) 'Water availability and land subsidence in the Central Valley, California, USA', *Hydrogeology Journal*, 24(3), pp. 675–684. Available at: https://doi.org/10.1007/s10040-015-1339-x.
25. Fernandez-Bou, A.S., Rodríguez-Flores, J.M., Guzman, A., Ortiz-Partida, J.P., Classen-Rodriguez, L.M., Sánchez-Pérez, P.A., Valero-Fandiño, J., Pells, C., Flores-Landeros, H., Sandoval-Solís, S., Characklis, G.W., Harmon, T.C., McCullough, M. and Medellín-Azuara, J. (2023) 'Water, environment, and socioeconomic justice in California: A multi-benefit cropland repurposing framework', *Science of The Total Environment*, 858, p. 159963. Available at: https://doi.org/10.1016/j.scitotenv.2022.159963.
26. Hanak, E. (2003) *Who should be allowed to sell water in California? third-party issues and the water market*. San Francisco, Calif: Public Policy Institute of California
27. Hanak, E. and Lund, J.R. (2012) 'Adapting California's water management to climate change', *Climatic Change*, 111(1), pp. 17–44. Available at: https://doi.org/10.1007/s10584-011-0241-3.
27. Hannah, W., Sandra, B., Daniel, M., Joseph, C., Philip A.M., B., Helen E., D. and William R., H. (2020) 'Agricultural managed aquifer recharge — water quality factors to consider', *California Agriculture*, 74(3), pp. 144–154. Available at: https://doi.org/10.3733/ca.2020a0020.
28. Hellerstein, D.M. (2017) 'The US Conservation Reserve Program: The evolution of an enrollment mechanism', *Land Use Policy*, 63, pp. 601–610. Available at: https://doi.org/10.1016/j.landusepol.2015.07.017.
29. Hernandez, R.R., Easter, S.B., Murphy-Mariscal, M.L., Maestre, F.T., Tavassoli, M., Allen, E.B., Barrows, C.W., Belnap, J., Ochoa-Hueso, R., Ravi, S. and Allen, M.F. (2014) 'Environmental impacts of utility-scale solar energy'. Available at: https://doi.org/10.1016/j.rser.2013.08.041.

30. Hernandez, R.R., Hoffacker, M.K., Murphy-Mariscal, M.L., Wu, G.C., Allen, M.F., 2015. Solar energy development impacts on land cover change and protected areas. Proc. Natl. Acad. Sci. U.S.A. 112, 13579–13584. https://doi.org/10.1073/pnas.1517656112
31. Hoffacker, M.K., Allen, M.F., Hernandez, R.R., 2017. Land-Sparing Opportunities for Solar Energy Development in Agricultural Landscapes: A Case Study of the Great Central Valley, CA, United States. Environ. Sci. Technol. 51, 14472–14482. https://doi.org/10.1021/acs.est.7b05110
32. Howitt, R. and Sunding, D. (2003). Water infrastructure and water allocation in California. *California Agriculture: Dimensions and Issues*, pp.181-190.
33. Hu, X., Shi, L., Lin, G. and Lin, L. (2021) 'Comparison of physical-based, data-driven and hybrid modeling approaches for evapotranspiration estimation', *Journal of Hydrology*, 601, p. 126592. Available at: https://doi.org/10.1016/j.jhydrol.2021.126592.
33. Imperial Irrigation District, (2014). Farm Unit Fallowing Program Description, 2014. Available at: https://www.iid.com/home/showpublisheddocument/8978/635648001335730000
34. IID. (2016). Imperial Irrigation District Fallowing Program Status Report; IID: Imperial, CA, USA, 2016. https://www.iid.com/home/showpublisheddocument/17119/636681351924530000.
35. Kelsey, R. *et al.* (2018) 'Groundwater sustainability in the San Joaquin Valley: Multiple benefits if agricultural lands are retired and restored strategically', *California Agriculture*, 72(3), pp. 151–154
36. Kibria, S., Masia, S., Sušnik, J. and Hessels, T.M. (2021) 'Critical comparison of actual evapotranspiration estimates using ground based, remotely sensed, and simulated data in the USA', *Agricultural Water Management*, 248, p. 106753. Available at: https://doi.org/10.1016/j.agwat.2021.106753.
37. Knipper, K., Anderson, M., Bambach, N., Melton, F., Ellis, Z., Yang, Y., Volk, J., McElrone, A.J., Kustas, W., Roby, M., Carrara, W., Castro, S., Kilic, A., Fisher, J.B., Ruhoff, A., Senay, G.B., Morton, C., Saa, S. and Allen, R.G. (2024) 'A comparative analysis of OpenET for evaluating evapotranspiration in California almond orchards', *Agricultural and Forest Meteorology*, 355, p. 110146. Available at: https://doi.org/10.1016/j.agrformet.2024.110146.
36. Lauer, A., English, D., Helton Richardson, M., 2023. How 'green energy' is threatening biodiversity, human health, and environmental justice: An example from the Mojave Desert, California. Sustainable Environment 9, 2192087. https://doi.org/10.1080/27658511.2023.2192087
37. Lortie CJ, Filazzola A, Kelsey R, Hart AK, Butterfield HS (2018) Better late than never: a synthesis of strategic land retirement and restoration in California. Ecosphere 9(8):e02367
38. Marwaha, N., Kourakos, G., Levintal, E. and Dahlke, H.E. (2021) 'Identifying Agricultural Managed Aquifer Recharge Locations to Benefit Drinking Water Supply in Rural Communities', *Water Resources Research*, 57(3), p. e2020WR028811. Available at: https://doi.org/10.1029/2020WR028811.
39. McComb, S., Powers, L.C. and Larsen, A.E. (2022) 'Evaluating climate-driven fallowing for ecological connectivity of species at risk', *Landscape Ecology*, 37(12), pp. 3059–3077. Available at: https://doi.org/10.1007/s10980-022-01522-9.

40. Medellín-Azuara, J., Escriva-Bou, A., Abatzoglou, J.A., Viers, J.H, Cole, S.A., Rodríguez-Flores, J.M., and Sumner, D.A. (2022). Economic Impacts of the 2021 Drought on California Agriculture. Preliminary Report. University of California, Merced. Available at http://drought.ucmerced.edu
41. Melton F., *et al.* Fallowed area mapping for drought impact reporting: 2015 assessment of conditions in the California Central Valley. NASA Ames Research Center. (2015). https://nex.nasa.gov/static/media/other/ Central_Valley_Fallowing_Data_Report_14Oct2015.pdf.
42. Miao, R., Feng, H., Hennessy, D.A. and Du, X. (2016) 'Assessing Cost-effectiveness of the Conservation Reserve Program (CRP) and Interactions between the CRP and Crop Insurance', *Land Economics*, 92(4), pp. 593–617. Available at: https://doi.org/10.3368/le.92.4.593.
43. Newman, G.D., Smith, A.L. and Brody, S.D. (2017) 'Repurposing Vacant Land through Landscape Connectivity', *Landscape Journal*, 36(1), pp. 37–57. Available at: https://doi.org/10.3368/lj.36.1.37.
44. O'Geen, A.T., Saal, M., Dahlke, H., Doll, D., Elkins, R., Fulton, A., Fogg, G., Harter, T., Hopmans, J.W., Ingels, C., Niederholzer, F., Solis, S.S., Verdegaal, P., Walkinshaw, M., 2015. Soil suitability index identifies potential areas for groundwater banking on agricultural lands. Cal Ag 69, 75–84. https://doi.org/10.3733/ca.v069n02p75
45. Owley, J., Morris, A.W., 2019. The New Agriculture: From Food Farms to Solar Farms. Columbia Journal of Environmental Law Vol. 44 No. 2 (2019): Volume 44.2. https://doi.org/10.7916/CJEL.V44I2.1859
46. Pearce, D., Strittholt, J., Watt, T., Elkind, E.N., 2016. A PATH FORWARD: Identifying Least-Conflict Solar PV Development in California's San Joaquin Valley.
47. Peterson, C., Pittelkow, C. and Lundy, M. (2022) *Exploring the Potential for Water- Limited Agriculture in the San Joaquin Valley*. 2022: Public Policy Institute of California.
48. PVID-MWD. (2004). PVID-MWD Forbearance and Fallowing Program Term Sheet for Forbearance and Fallowing Program Agreement. 2004, p. 2. Available at: https://www.mwdh2o.com/media/18478/palo-verde-irrigation-dist-mwd-forbearanceandfallow ingprogramagreement.pdf.
49. Quandt, A., Larsen, A.E., Bartel, G., Okamura, K. and Sousa, D. (2023) 'Sustainable groundwater management and its implications for agricultural land repurposing', *Regional Environmental Change*, 23(4), p. 120. Available at: https://doi.org/10.1007/s10113-023-02114-2.
50. Rega, C., Helming, J. and Paracchini, M.L. (2019) 'Environmentalism and localism in agricultural and land-use policies can maintain food production while supporting biodiversity. Findings from simulations of contrasting scenarios in the EU', *Land Use Policy*, 87, p. 103986. Available at: https://doi.org/10.1016/j.landusepol.2019.05.005.
51. Rosevelt, C. *et al.* (2016) 'Drought Impacts on Agricultural Production and Land Fallowing in California's Central Valley in 2015'. Available at: https://ntrs.nasa.gov/citations/20160012760 (Accessed: 6 July 2024)
52. Sanden, B. (2010). Scientific irrigation scheduling in permanent crops: process, planning, programs & pressure bomb. Kern Irrigation Workshop. Kern Soil & Water Newsletter. 8 April 2010.
53. Schoeneberger, M.M., Bentrup, G., Patel-Weynand, T. (2017). Agroforestry: Enhancing Resiliency in U.S. Agricultural Landscapes Under Changing

Conditions (No. WO-GTR-96). U.S. Department of Agriculture, Forest Service, Washington, DC. https://doi.org/10.2737/WO-GTR-96
54. Scudiero, E., Corwin, D., Anderson, R. and Skaggs, T. (2016) 'Moving Forward on Remote Sensing of Soil Salinity at Regional Scale', *Frontiers in Environmental Science*, 4. Available at: https://doi.org/10.3389/fenvs.2016.00065.
54. SDCWA. (2020). Colorado River Water Transfer Agreement; San Diego County Water Authority: San Diego, CA, USA, 2020. Available at: https://www.sdcwa.org/wp-content/uploads/2020/11/watertransfer-fs.pdf
55. State Water Resources Control Board (State Water Board). (2023). *GAMA - GIS | California State Water Resources Control Board*. Available at: https://www.waterboards.ca.gov/gama/gama-gis.html.
55. Senay, G. B. (2018). Satellite psychrometric formulation of the Operational Simplified Surface Energy Balance (SSEBop) model for quantifying and mapping evapotranspiration. Applied Engineering in Agriculture, 34(3), 555-566. https://doi.org/10.13031/aea.12614
56. Senay, G. B., Budde, M., Verdin, J. P., & Melesse, A. M. (2007). A coupled remote sensing and simplified surface energy balance approach to estimate actual evapotranspiration from irrigated fields. Sensors, 7(6), 979-1000
57. Stid, Jacob T, Shukla, S., Anctil, A., Kendall, A.D., Hyndman, D.W., 2022. Implications of Agriculturally Co-Located Solar PV Installations on the FEW Nexus in the Central Valley, in: 2022 IEEE 49th Photovoltaics Specialists Conference (PVSC). Presented at the 2022 IEEE 49th Photovoltaics Specialists Conference (PVSC), IEEE, Philadelphia, PA, USA, pp. 0144–0144. https://doi.org/10.1109/PVSC48317.2022.9938746
58. Sunding, David, and David Roland-Holst. "Blueprint Economic Impact Analysis: Phase One Results." (2020): n. pag. Web.
59. Ulibarri, N., Escobedo Garcia, N., Nelson, R.L., Cravens, A.E. and McCarty, R.J. (2021) 'Assessing the Feasibility of Managed Aquifer Recharge in California', *Water Resources Research*, 57(3), p. e2020WR029292. Available at: https://doi.org/10.1029/2020WR029292.
60. USDA National Agricultural Statistics Service Cropland Data Layer. (2020). Published crop-specific data layer. USDA-NASS, Washington, DC. Available at: https://nassgeodata.gmu.edu/CropScape/.
61. Volk, J.M., Huntington, J.L., Melton, F.S., Allen, R., Anderson, M., Fisher, J.B., Kilic, A., Ruhoff, A., Senay, G.B., Minor, B., Morton, C., Ott, T., Johnson, L., Comini de Andrade, B., Carrara, W., Doherty, C.T., Dunkerly, C., Friedrichs, M., Guzman, A., Hain, C., Halverson, G., Kang, Y., Knipper, K., Laipelt, L., Ortega-Salazar, S., Pearson, C., Parrish, G.E.L., Purdy, A., ReVelle, P., Wang, T. and Yang, Y. (2024) 'Assessing the accuracy of OpenET satellite-based evapotranspiration data to support water resource and land management applications', *Nature Water*, 2(2), pp. 193–205. Available at: https://doi.org/10.1038/s44221-023-00181-7.
62. Wanniarachchi, S. and Sarukkalige, R. (2022) 'A Review on Evapotranspiration Estimation in Agricultural Water Management: Past, Present, and Future', *Hydrology*, 9(7), p. 123. Available at: https://doi.org/10.3390/hydrology9070123.
63. Wong, A.J., Jin, Y., Medellín-Azuara, J., Paw U, K.T., Kent, E.R., Clay, J.M., Gao, F., Fisher, J.B., Rivera, G., Lee, C.M., Hemes, K.S., Eichelmann, E., Baldocchi, D.D. and Hook, S.J. (2021) 'Multiscale Assessment of Agricultural

Consumptive Water Use in California's Central Valley', *Water Resources Research*, 57(9), p. e2020WR028876. Available at: https://doi.org/10.1029/2020WR028876.
61. Żarczyński, P.J. *et al.* (2023) 'The Role of Fallows in Sustainable Development', *Agriculture*, 13(12), p. 2174. Available at: https://doi.org/10.3390/agriculture13122174.

CHAPTER 5: CONCLUSION

This dissertation investigates the evolving dynamics of water use and management under changing climate in the diverse agricultural systems within the San Joaquin Valley (SJV) of California. The findings from three distinct yet interconnected studies provide understandings into the challenges and potential adaptation strategies for sustainable agricultural practices in the face of dwindling water resources and climate-induced challenges. By employing large scale process-based crop and hydrology model, the study provided actionable insights that can contribute to the sustainable management of water resources and agricultural practices in the SJV.

In the first study, the change in specialty tree crop water use due to varying climate and atmospheric CO_2 was studied by taking the case of almond and pistachio, which are among the highest water consuming in SJV. The impact of these changes on the phenology, water needs, and potential yield of these crops were assessed. The findings revealed a complex relationship between climate change, water availability, and crop management. The results highlighted that pistachios are more vulnerable to changes compared to almonds. This study suggested that elevated CO_2 can offset the effect of warming on irrigation demand, from which almonds will benefit more compared to pistachios. The management adaptations and the selection of drought-resistant crop varieties or switching to less water-intensive crops could mitigate some of the predicted vulnerabilities, thus aiding farm and water managers in devising long-term sustainable strategies. In the second study, climate change effect is scaled up for other crops to estimate the water demand changes at hydrologic basin scales. The interconnectedness of climate, hydrology, and water supply revealed the implications of rising temperatures, changing precipitation patterns and snowmelt on the reliability of water source for agriculture in the SJV. The results emphasized on the risks posed by inflexibility in the current cropping patterns and surface storage capacities, advising the need for adaptive water management strategies. The study underscored the importance of comprehensively understanding the agricultural system's vulnerabilities at a basin scale. Thus, providing insights for water managers to anticipate and mitigate future supply-demand discrepancies and develop more resilient agricultural planning.

Climate change will also have implications on water conserving strategies like farmland land fallowing for alternate use. The third paper examined land repurposing strategies as methods for water conservation under different climate scenarios. It evaluated the potential water savings from alternative land uses for habitat restoration, groundwater recharge, and renewable energy development, highlighting the significant benefits these strategies could offer. The research demonstrated that groundwater recharge in the suitable habitat corridors could effectively reduce water demand, augment water supply, while enhancing ecological and environmental

sustainability. By providing precise water reduction values for key crops, the study provides understandings that can inform targeted agricultural planning, implementation challenges, policymaking, incentive programs and promoting conservation in water-scarce region of SJV.

Agricultural water use under climate change reveals several key findings. The effects of climate change on crop phenology significantly influence changes in water demand and challenge the viability of tree crops, highlighting the need for more focus on managing water supply rather than just demand. Adaptation on the demand side is crucial, as different crops offer varying levels of flexibility when considered for retirement. However, the longevity of perennial crops can increase capital investment, adding another layer of complexity to water management strategies. Effective management will require a balanced approach that considers both the flexibility and the long-term financial implications of perennial crop investment. These findings elucidated the multifaceted challenges and opportunities in managing water resources for agriculture under climate change. They underscore the necessity for integrated, adaptive management approaches that consider crop-specific water needs, climatic conditions, and the broader socio-economic impacts. Future research should focus on long-term impacts of proposed land use conversions, including economic and environmental outcomes, to refine and enhance the effectiveness of water management practices. The results from these studies provide a starting point to inform further research and policy development aimed at ensuring the resilience and sustainability of agricultural systems in the face of climate change.

APPENDICES

Appendix A: Supplemental Information for Chapter 2

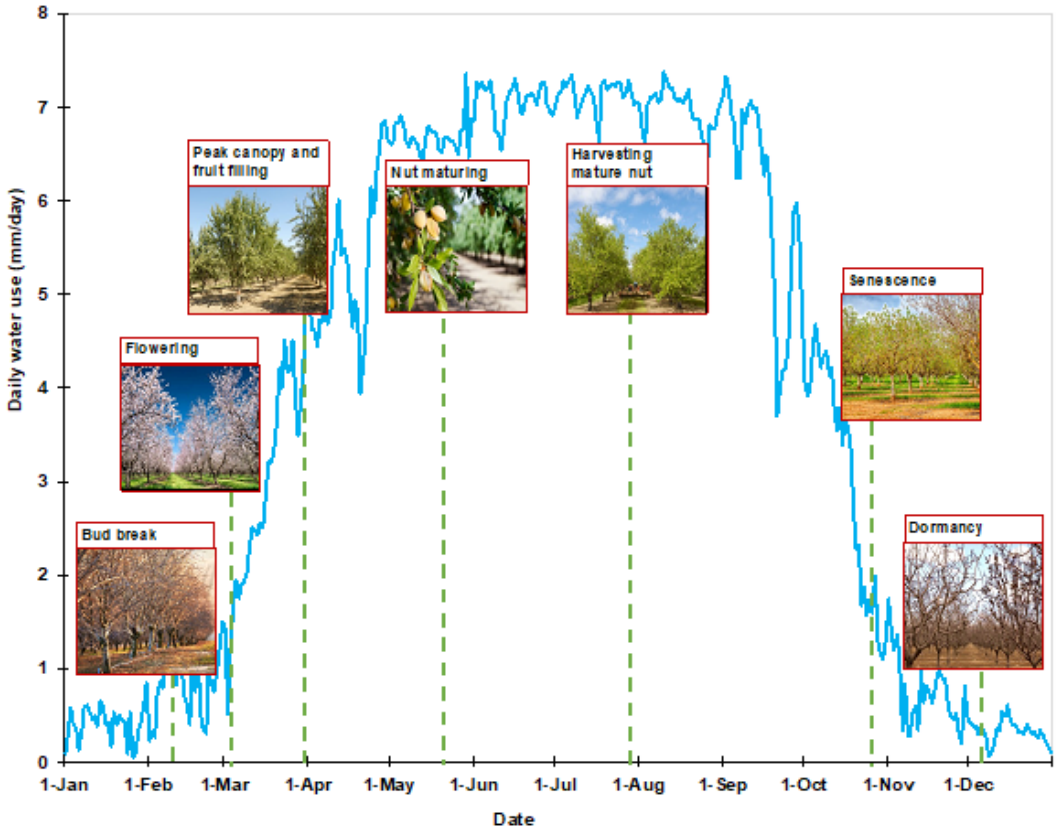
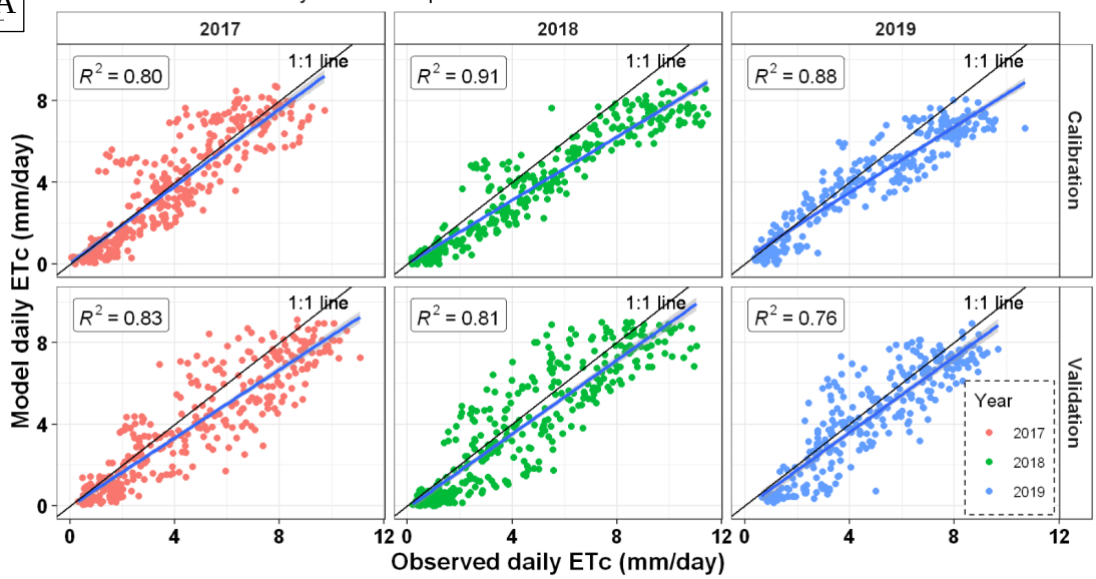
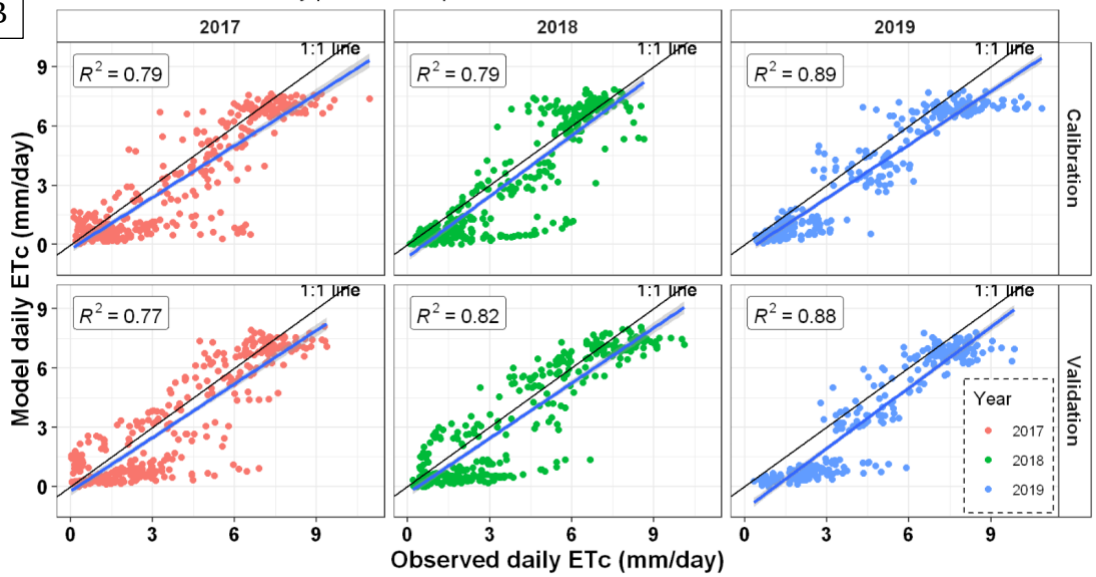


Figure S1: Representation of annual life cycle's phenological stages and daily water use of nut trees. Photos of each phenological stage of annual growth stages for almond tree crop and an average daily water use throughout the year (crop evapotranspiration). Green dashed lines depict the approximate date of occurrence of each stage for almond crop.

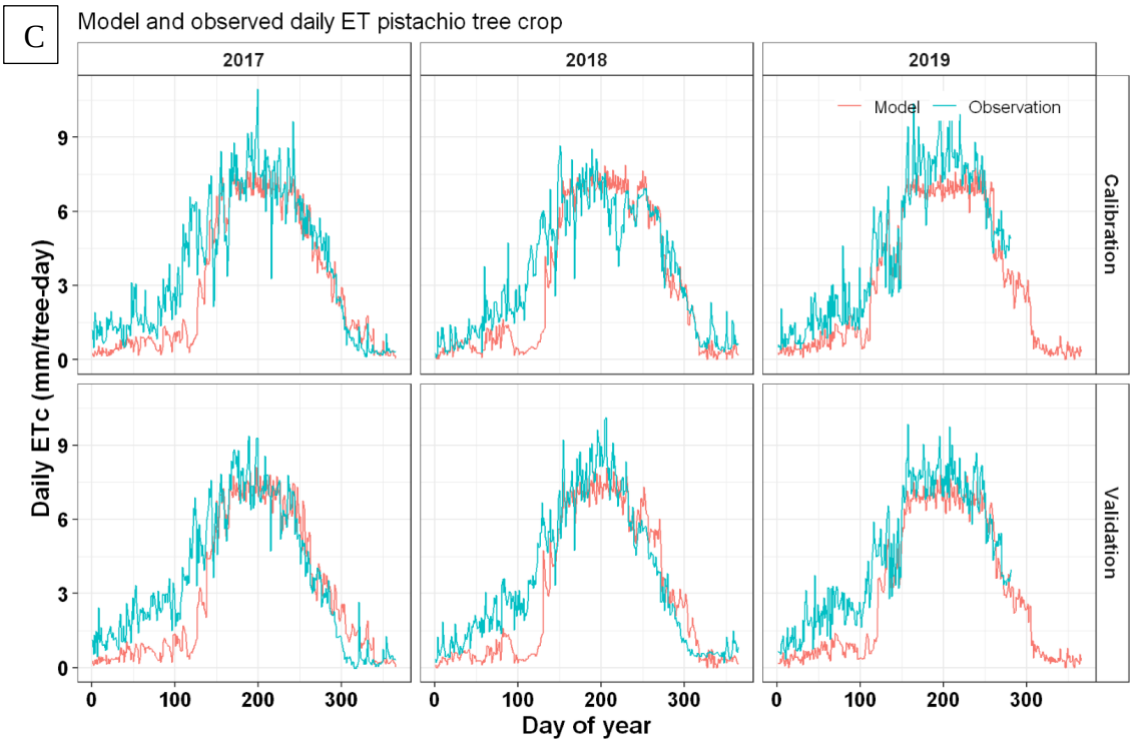
A


Model and observed daily almond crop ET
2017
2018
2019
R^2 = 0.80
R^2 = 0.91
R^2 = 0.88
R^2 = 0.83
R^2 = 0.81
R^2 = 0.76
1:1 line
Calibration
Validation
Year
2017
2018
2019
Model daily ETc (mm/day)
Observed daily ETc (mm/day)
0
4
8
12

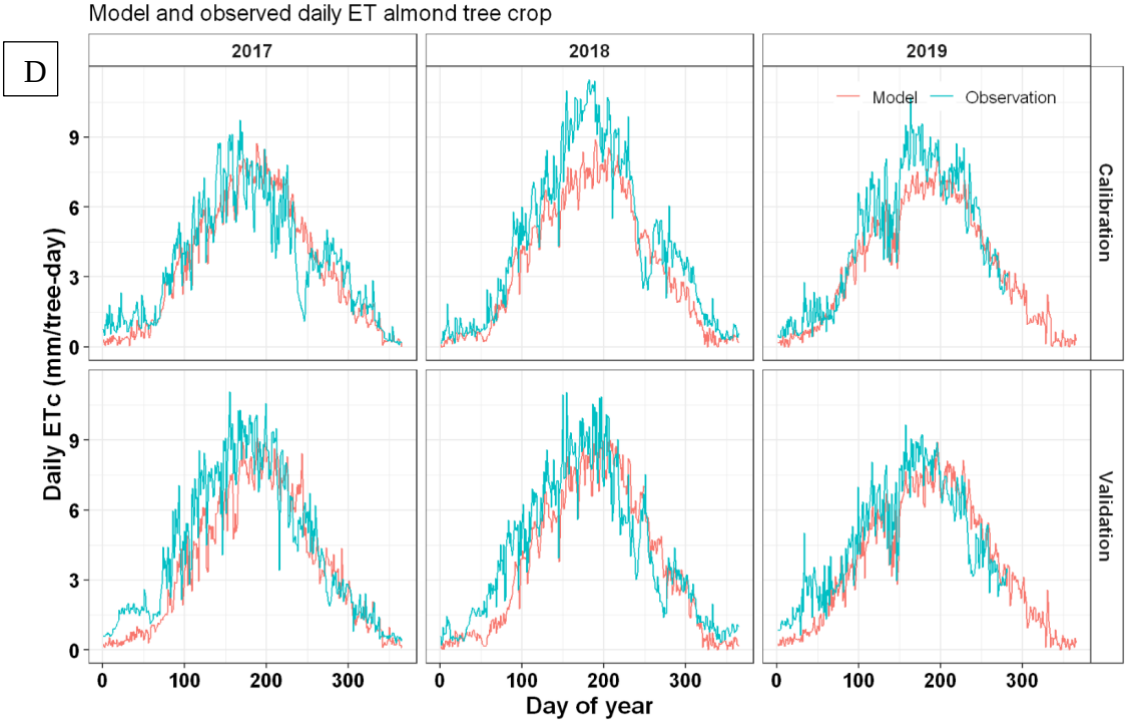
B


Model and observed daily pistachio crop ET
2017
2018
2019
R^2 = 0.79
R^2 = 0.79
R^2 = 0.89
R^2 = 0.77
R^2 = 0.82
R^2 = 0.88
1:1 line
Calibration
Validation
Year
2017
2018
2019
Model daily ETc (mm/day)
Observed daily ETc (mm/day)
0
3
6
9

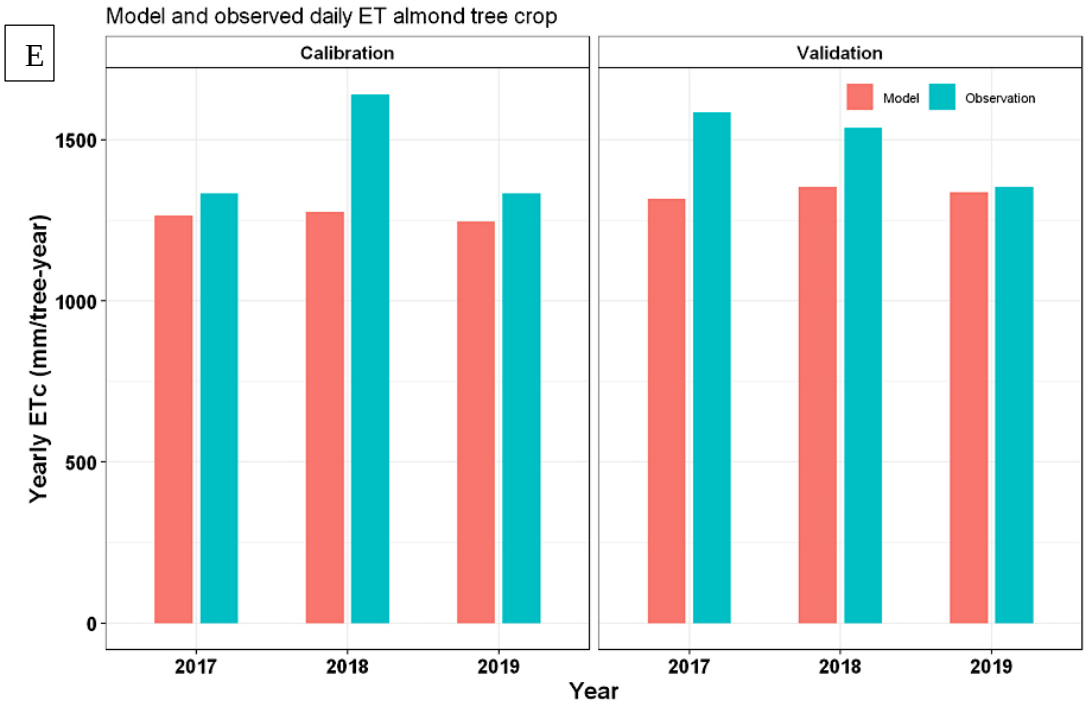
C


Model and observed daily ET pistachio tree crop
2017
2018
2019
Model
Observation
Calibration
Validation
Daily ETc (mm/tree-day)
0
3
6
9
0
100
200
300
Day of year

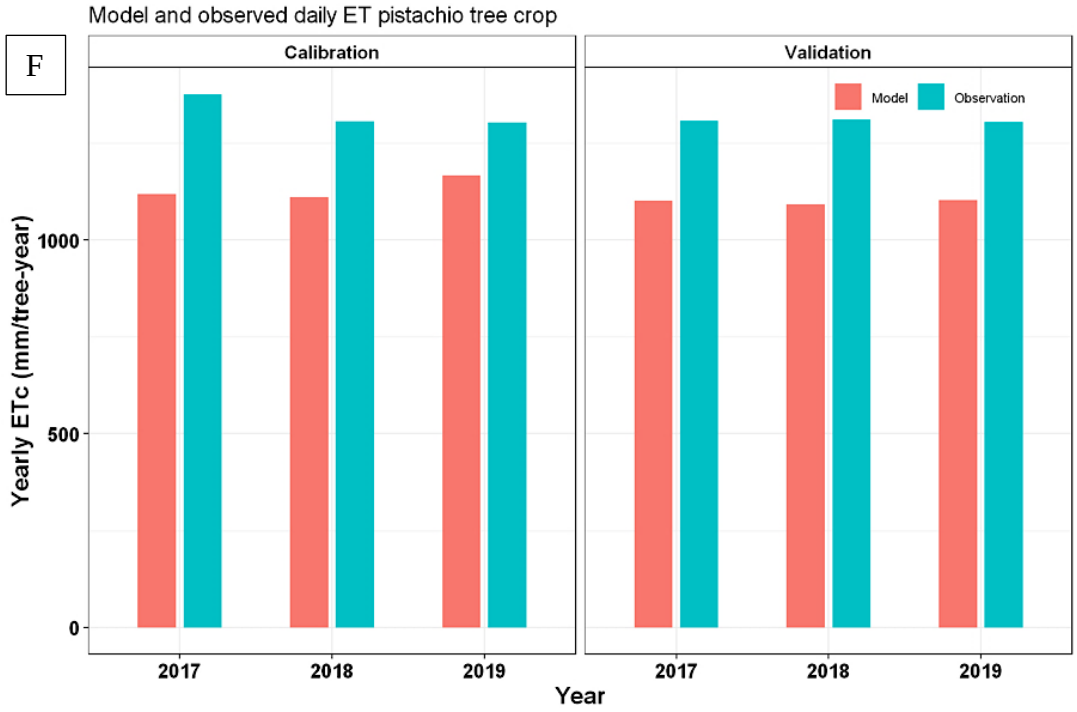
D


Model and observed daily ET almond tree crop
2017
2018
2019
Model
Observation
Calibration
Validation
Daily ETc (mm/tree-day)
0
3
6
9
0
100
200
300
Day of year

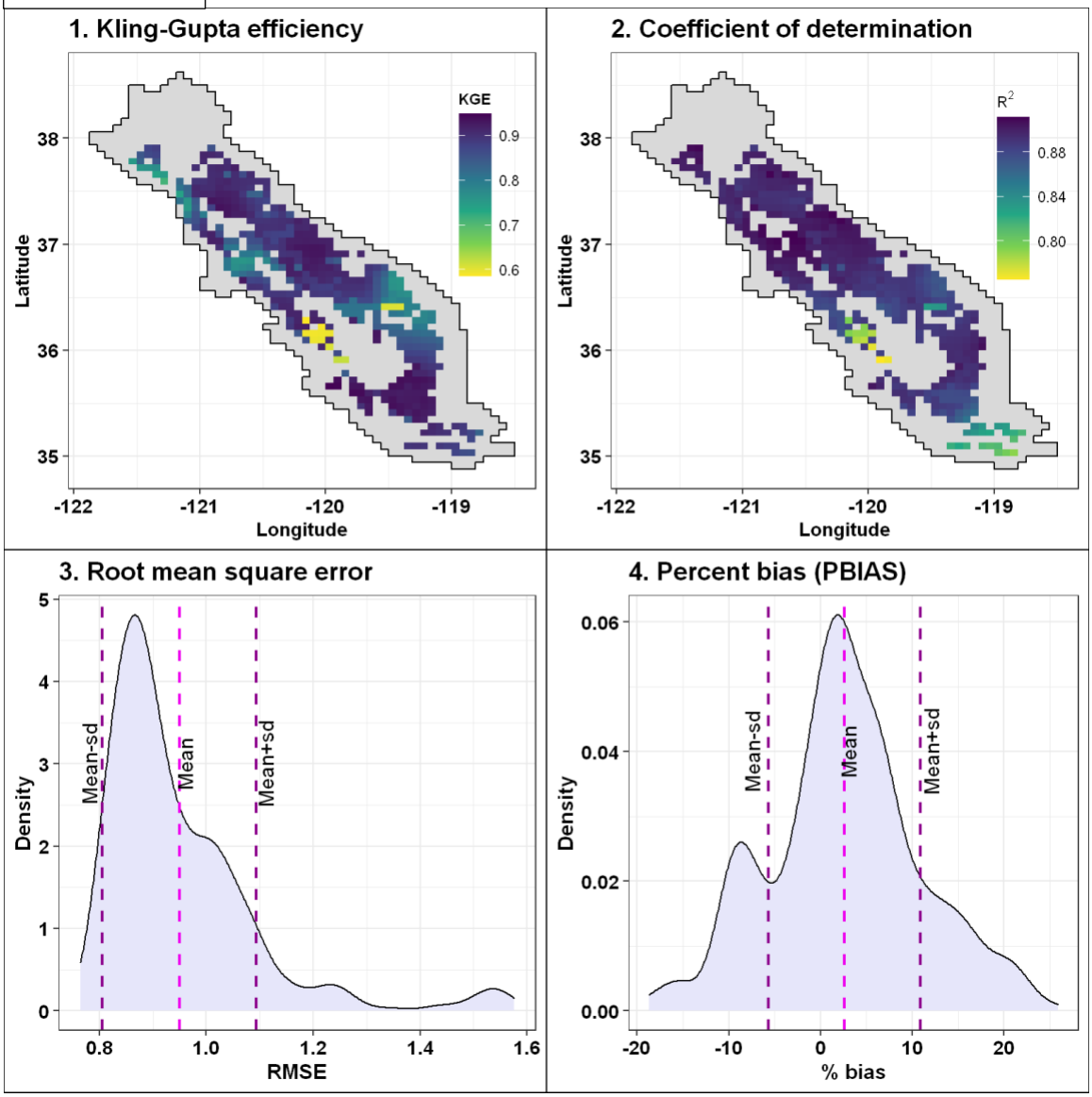
E


Model and observed daily ET almond tree crop
Calibration
Validation
Model
Observation
Yearly ETc (mm/tree-year)
1500
1000
500
0
2017
2018
2019
Year

F


Model and observed daily ET pistachio tree crop
Calibration
Validation
Model
Observation
Yearly ETc (mm/tree-year)
1000
500
0
2017
2018
2019
Year

G-Almond


1. Kling-Gupta efficiency
KGE
0.9
0.8
0.7
0.6
Latitude
Longitude
38
37
36
35
-122
-121
-120
-119
2. Coefficient of determination
R2
0.88
0.84
0.80
3. Root mean square error
Density
RMSE
Mean-sd
Mean
Mean+sd
0.8
1.0
1.2
1.4
1.6
4. Percent bias (PBIAS)
% bias
0.06
0.04
0.02
0.00
-20
-10
0
10
20

H- Pistachio

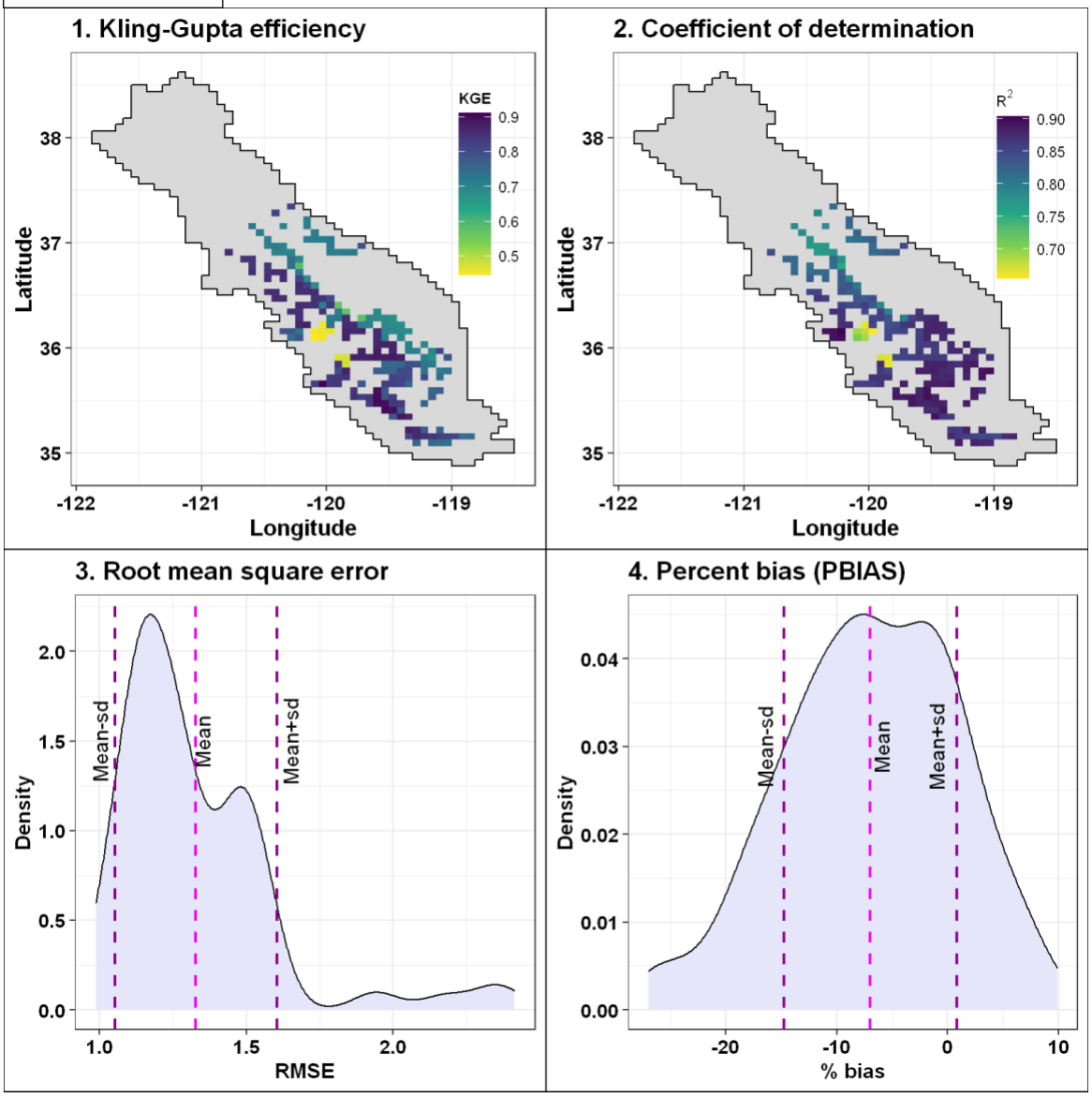


Figure S2: Calibration and validation results (A-F) using Eddy covariance flux tower data. Goodness of fit model results for all grids compared to Spatial CIMIS ETc for almond (G, left) and pistachio grids (H, right).

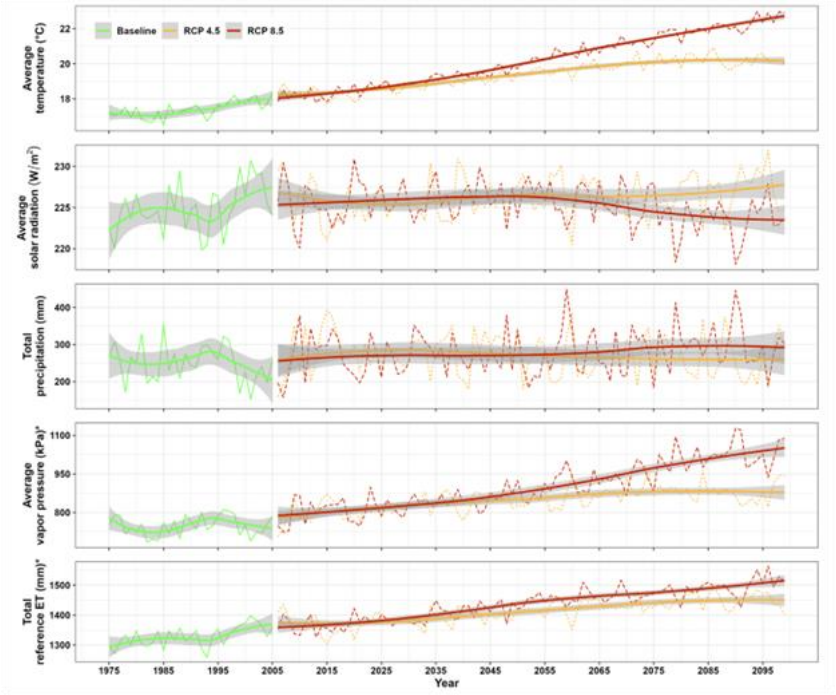


Figure S3: Annual average of mean temperature, solar radiation, total precipitation, and vapor pressure for the study area averaged from 4 GCMs. The dark grey area indicates the 0.95 confidence interval.

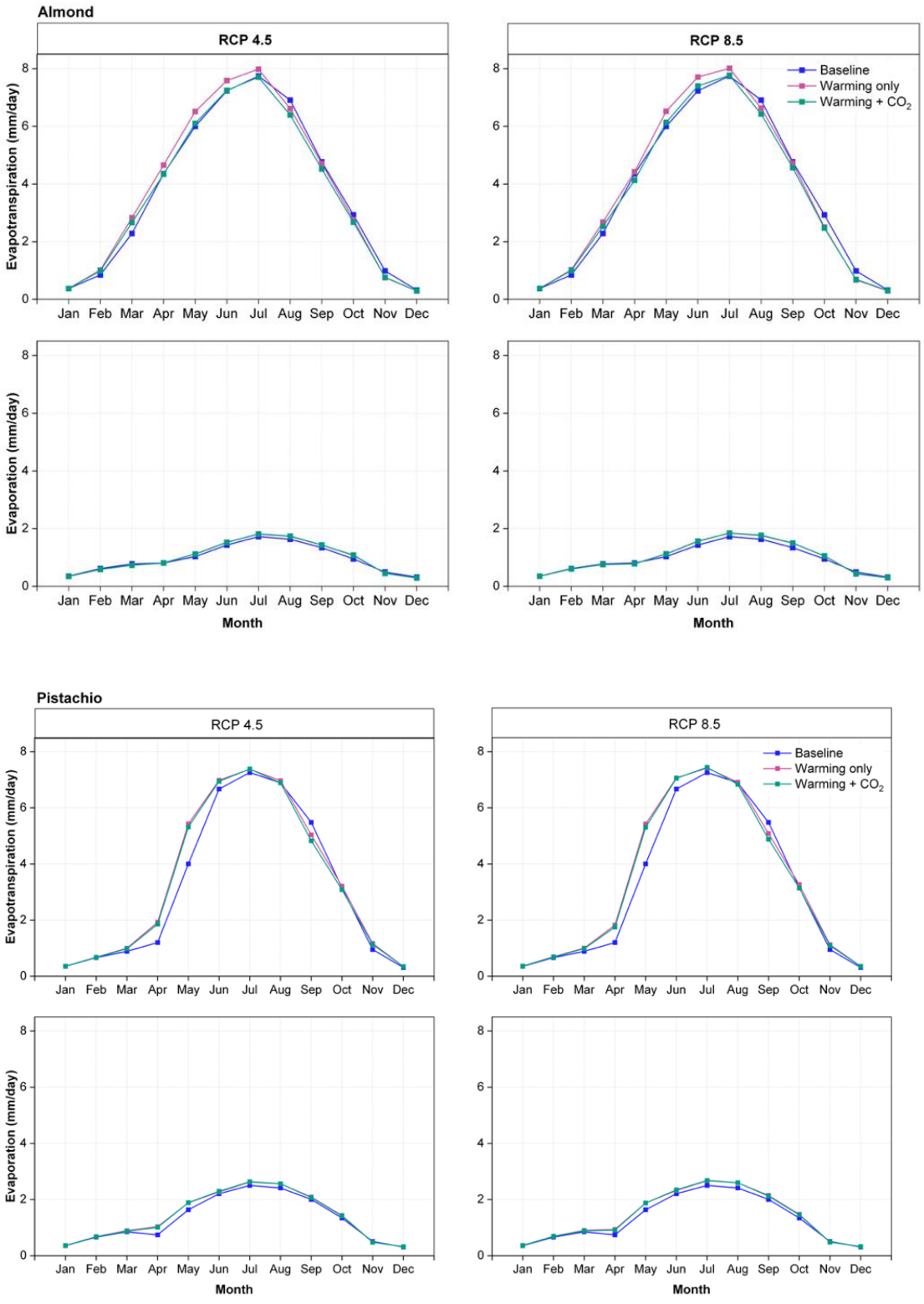


Figure S4: Almond and pistachio crops daily average evapotranspiration and evaporation for baseline (blue), warming only (magenta) and warming + CO_2 (green) in RCP4.5 and RCP8.5 scenarios.

Table S1: Input data and sensitive parameters table

Data	Description	Source
Met. Data	Daily precipitation, minimum and maximum temperature, wind speed, shortwave solar radiation, vapor pressure	GridMET (Abatzoglou and Brown, 2012)
Future forcing	MACA downscaled GCMs climate projection for the period 2020-2099.	4 CMIP5 GCM/emission scenario combinations as recommended by DWR
Soil	Soil texture, saturated hydrologic conductivity, bulk density, organic matter	STATSGO2, Maurer *et al*., 2002
Crop parameters	Phenology (dates for emergence date, peak leaf area index, beginning of flowering, grain filling, maturity, dormancy); critical temperatures, leaf water potential, peak leaf area index, max. root depth, average yield, moisture content (%).	Field data, existing models, and literature, USDA-NASS, UCANR field trials, county reports University of California Agriculture extension and USDA
Irrigation	Type of irrigation technology,	DWR dominant irrigation type for major crops in California (2010)
Vegetation parameter	Spatial distribution of vegetation and crops, Leaf area index of other natural vegetation and crops, Rood depth (VIC default)	USDA-Crop Data Layer (2020), MODIS data were taken from Bohn and Vivoni (2019)
Atm. CO2 concentration	Baseline historical and future scenarios	IPCC, 2014; Meinshausen *et al.*, 2011
Sensitive parameters	Maximum canopy cover, crop coefficient (kc), leaf water potential, daily maximum water uptake, transpiration use efficiency	Rajagopalan *et al*. (2018), Adam *et al*. (2021), Hall *et al*. (2022) and this study

Table S2: Annual average climate variables and reference ET for Baseline future climate change scenarios

	Average temperature	Maximum temperature	Minimum temperature	Solar radiation	Vapor pressure	Precipitation	Reference ET*	Days below 0°C	Days above 32°C
CanESM2	17.5	24.9	10.1	225	740	236	1336	26	6
CNRM-CM5	17.6	25	10.2	225	756	247	1343	29	6
HadGEM2-ES365	17.3	24.6	9.9	225	752	259	1322	29	6
MIROC5	17.2	24.6	9.9	224	742	259	1316	27	6
Baseline ensemble	**17.4**	**24.8**	**10**	**225**	**748**	**250**	**1329**	**28**	**6**
CanESM2	19.6	27	12.2	223	869	273	1389	9	28
CNRM-CM5	19.1	26.5	11.7	225	864	315	1401	12	18
HadGEM2-ES365	19.6	27.1	12	229	856	262	1428	14	26
MIROC5	19.2	26.9	11.6	229	807	232	1428	15	25

RCP 4.5 ensemble	**19.4**	**26.9**	**11.9**	**226**	**849**	**271**	**1412**	**13**	**24**
CanESM2	20.6	28	13.2	221	939	307	1412	8	51
CNRM-CM5	19.9	27.2	12.6	224	913	318	1428	10	31
HadGEM2-ES365	20.6	28.1	13	229	912	259	1465	11	48
MIROC5	19.8	27.4	12.1	228	842	233	1436	13	34
RCP 8.5 ensemble	**20.2**	**27.7**	**12.7**	**225**	**901**	**279**	**1435**	**11**	**41**

*Calculated using model

Appendix B: Supplemental Information for Chapter 3

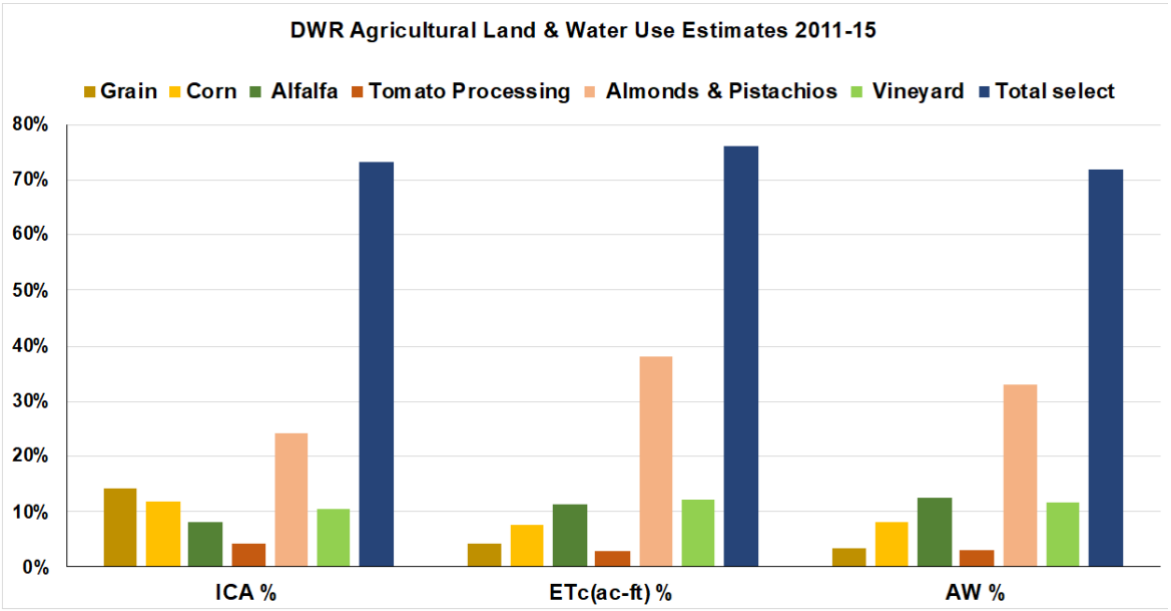


Figure S1: The average of select crops' percent of irrigated crop area (ICA), crop evapotranspiration (ETc), and applied water (AW) in SJV counties (sourced from DWRb, 2018)

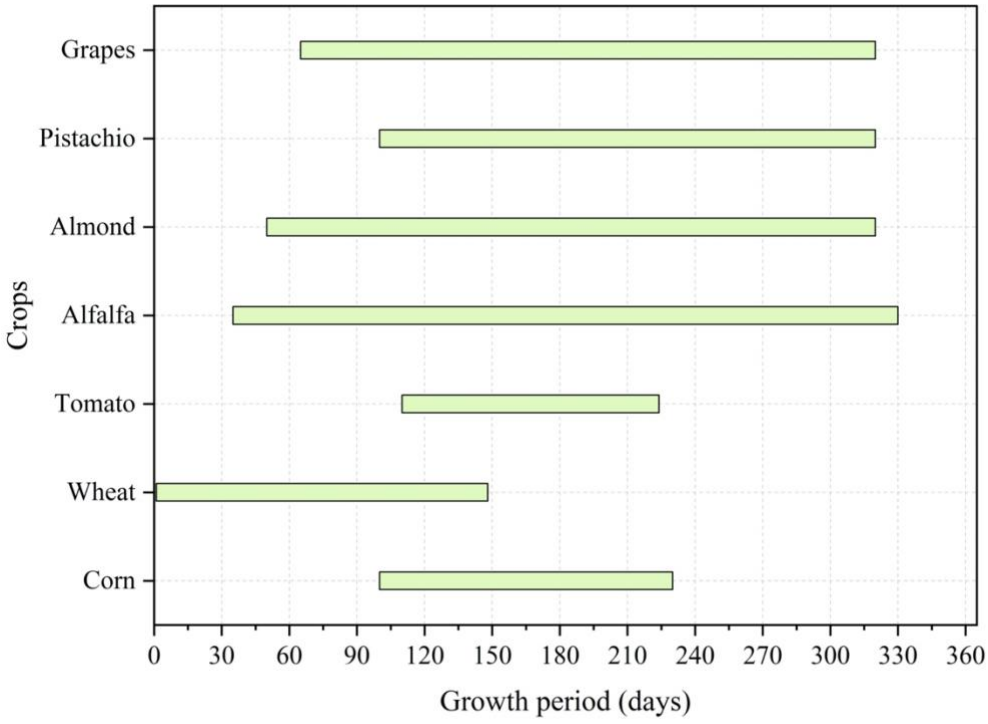


Figure S2: traditional active growth period average for seven main crops in San Joaquin Valley

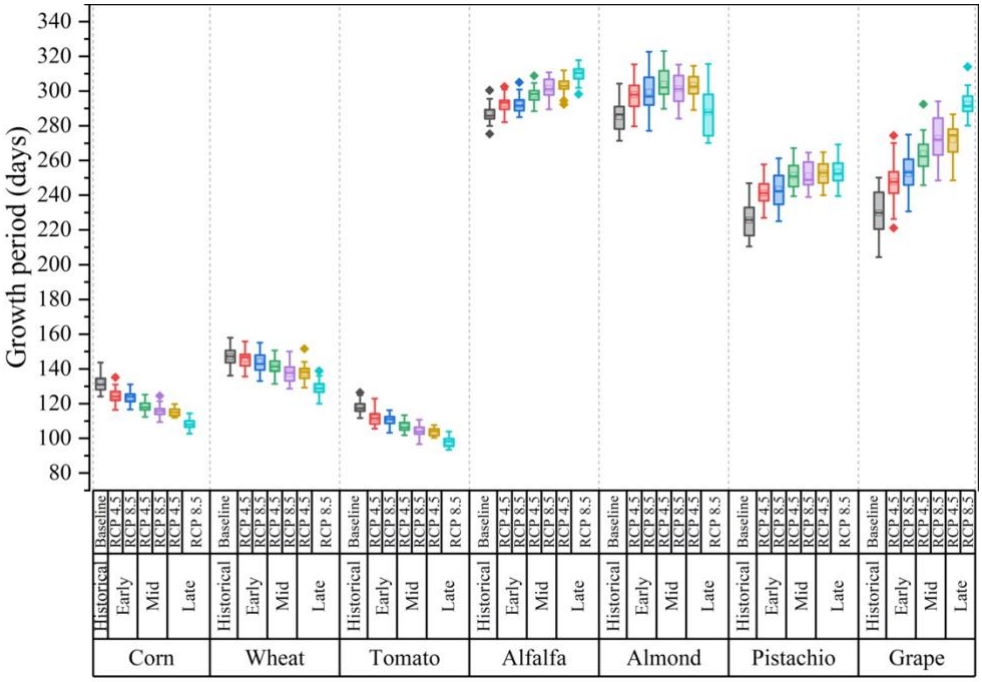
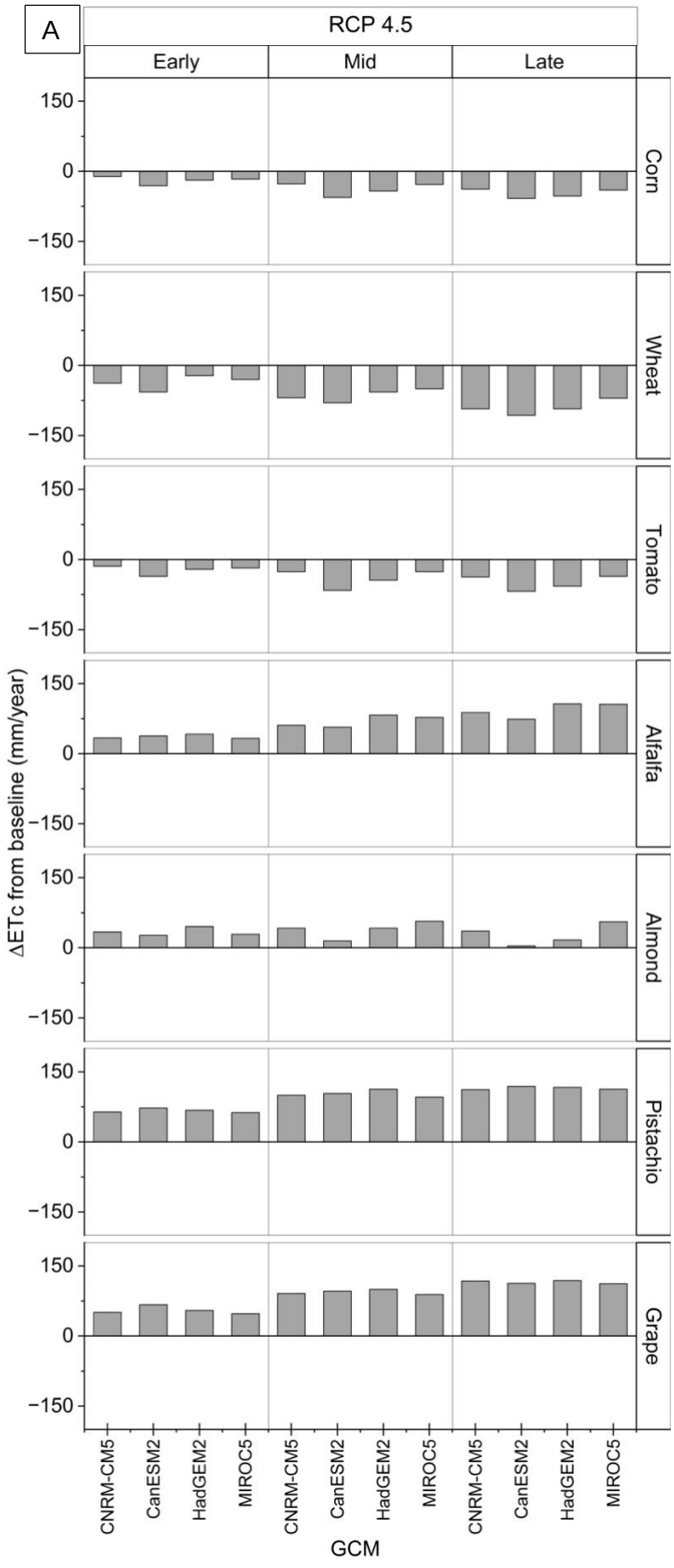


Figure S3: Average range of number of days of active period for each crop in early, mid and late periods of RCP4.5 and RCP8.5


A
RCP 4.5
Early
Mid
Late
Corn
Wheat
Tomato
Alfalfa
Almond
Pistachio
Grape
150
0
−150
ΔETc from baseline (mm/year)
CNRM-CM5
CanESM2
HadGEM2
MIROC5
GCM

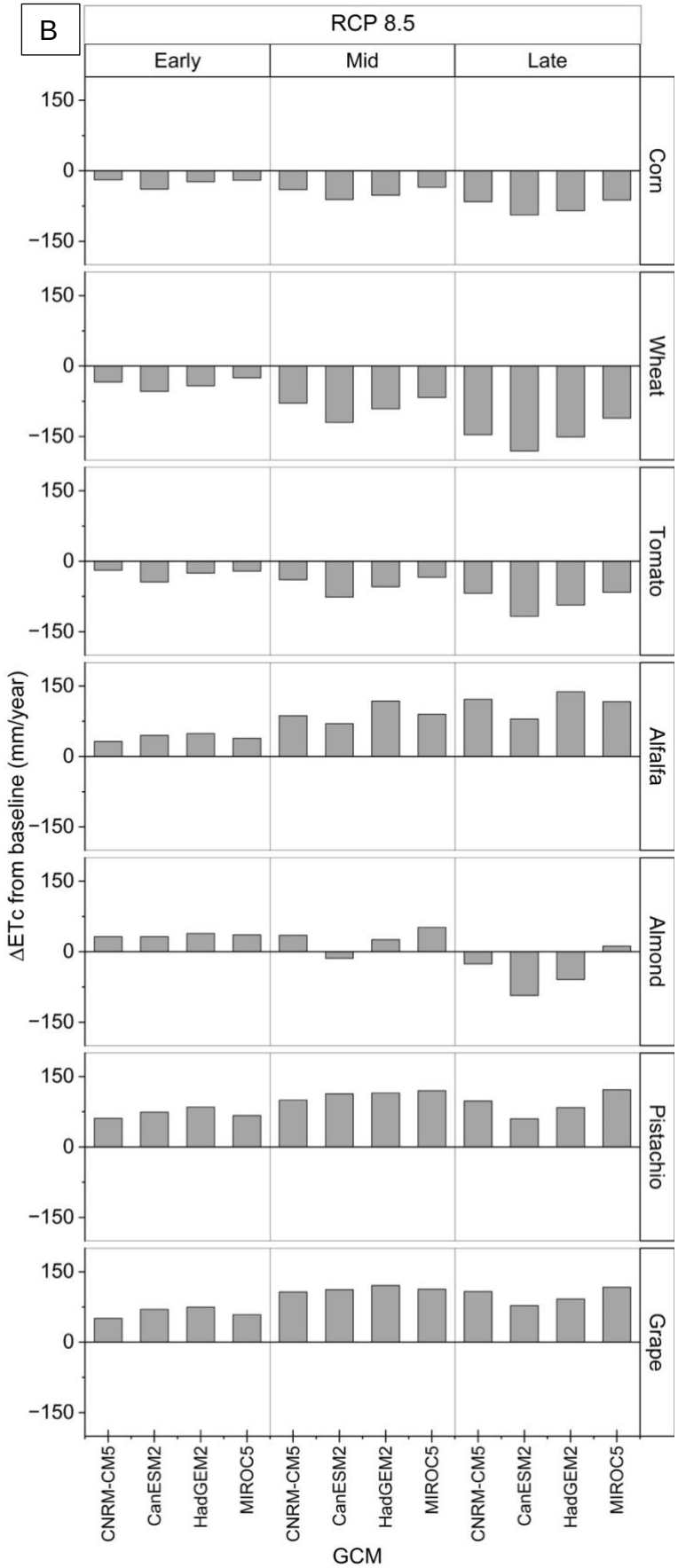


Figure S4: Crop water use for seven averaged for the each of three time periods (x-axis, top) from four GCM (x-axis, bottom) under RCP4.5 (A) and RCP8.5 (B) climate change scenarios.

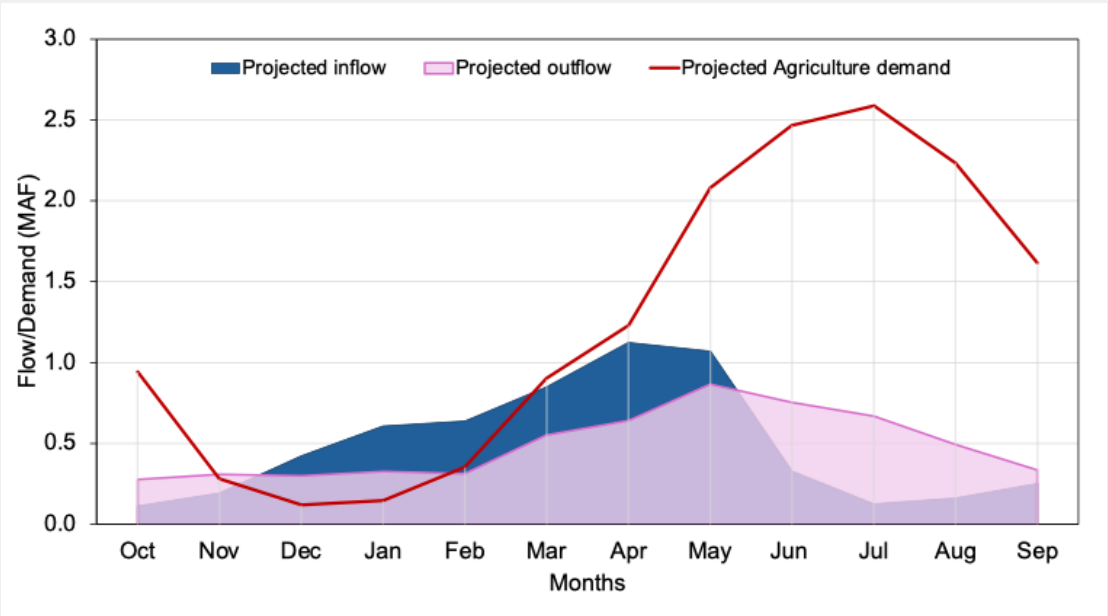


Figure S5: Projected future inflow and outflow to 13 major reservoirs along with future demand showing the peak months of agriculture demand (red line) for reference.

Table S1: Main input and calibration data for the model

		Corn	Wheat	Tomato	Alfalfa	Almond	Pistachio	Grapes
Phenology	Emergence	100	1	110	35	50	100	65
	Harvest/Dormancy date	230	148	224	330	320	320	320
	Seasonal length	130	147	114	295	270	220	255
	Base temperature (◦C)	10	7	10	5	5	7	10
	Cutoff temperature (◦C)	35	30	30	30	35	35	35
	Dormancy inducing days	-	-	-	8	8	8	8
	Dormancy inducing temperature (◦C)	-	-	-	14.5	15	15	15
Transpiration	Mid-season ET crop factor–kc	1.2	1.2	1.1	1.1	1.11	1.19	0.9
	Maximum water uptake	12	14	11	11	10	9	6.5
	maximum canopy cover fraction	0.95	0.95	0.9	0.98	0.75	0.61	0.65
	Light extinction coefficient							
	Maximum root depths (m)							
Management	Irrigation type	Furrow	Center Pivot	Furrow	Flood	Drip	Drip	Drip
	Efficiency (%)	0.5	0.85	0.5	0.5	0.97	0.97	0.97
	Maximum application (mm/day)	250	30	250	250	30	30	30
	MAD	0.5	0.2	0.5	0.5	0.1	0.1	0.1

Table S2: Change in yearly ETc and number of active growth season for each crop from the baseline

Scenarios	Baseline	RCP 4.5	RCP 8.5	Baseline	RCP 4.5	RCP 8.5
Crops	**Growth length (in days)**	**Growth length change (in days)**	**Growth length change (in days)**	**ETc (mm/year)**	**% ETc change**	**% ETc change**
Corn	155	-20	-24	680	-6%	-9%
Wheat	179	-17	-22	554	-15%	-21%
Tomato	140	-19	-22	755	-10%	-12%
Alfalfa	298	10	12	1010	7%	8%
Almond	329	-6	-10	1360	5%	5%
Pistachio	263	18	19	1115	8%	9%
Grape	292	14	15	900	10%	12%

Table S3: Monthly ETc (in mm) for each crop in the baseline and climate change scenarios

	Baseline	RCP 4.5			RCP 8.5		
Crops	**Historical**	**Early**	**Mid**	**Late**	**Early**	**Mid**	**Late**
Corn							
Apr	23	26	26	28	26	28	30
May	98	124	143	154	118	152	183
Jun	230	238	244	247	242	247	247
Jul	232	210	185	167	209	168	117
Aug	80	53	32	24	49	26	14
Sep	16	8	6	6	8	6	
Wheat							
Dec	4	4	4	4	4	4	5
Jan	11	11	12	13	12	14	17
Feb	24	30	39	45	33	46	58
Mar	90	105	119	122	108	123	131
Apr	166	171	173	164	169	161	120
May	187	150	102	77	142	84	33
Jun	71	37	33	39	45	27	34
Jul	17	4					
Tomato							
Apr	16	18	19	19	18	19	20
May	73	91	105	113	86	112	136
Jun	206	213	221	226	218	225	226
Jul	235	237	240	238	238	237	203
Aug	186	140	92	69	131	76	44
Sep	44	34	6		38	7	
Alfalfa							
Oct	81	85	87	90	86	90	94
Nov	31	35	39	41	35	40	42
Dec	6	7	10	11	7	10	12
Jan							
Feb	19	20	22	23	21	22	25
Mar	63	73	87	91	78	91	98
Apr	111	101	91	91	97	94	102
May	134	147	150	149	146	149	150
Jun	146	151	157	161	154	161	162
Jul	162	161	168	172	163	168	161
Aug	146	152	155	158	151	156	152
Sep	115	119	121	124	120	125	126

Almond							
Oct	90	94	97	101	95	99	99
Nov	31	35	35	36	33	36	33
Dec	6	5	5	6	4	4	8
Jan	11	10	10	9	11	9	7
Feb	24	27	30	31	29	31	32
Mar	71	83	91	92	86	93	97
Apr	131	136	142	139	135	139	120
May	185	194	202	204	191	203	210
Jun	216	221	227	231	225	231	235
Jul	240	243	247	250	245	249	250
Aug	213	210	203	202	208	203	205
Sep	143	139	140	145	140	146	149
Pistachio							
Oct	96	96	98	102	96	101	105
Nov	29	33	36	40	33	38	41
Dec	6	5	8	10	7	8	10
Jan	0	1	2			3	
Feb	6	8	7	7	7	8	6
Mar	17	25	27	29	26	30	29
Apr	35	52	63	62	55	62	48
May	128	161	176	176	158	176	179
Jun	203	208	211	214	210	214	216
Jul	226	227	229	231	228	231	233
Aug	214	217	214	214	216	214	210
Sep	162	152	145	148	152	149	149
Grape							
Oct	76	78	80	84	79	83	79
Nov	23	27	28	31	26	29	27
Dec	6	5	6	6	5	5	7
Jan	12	7	6	7	6	6	5
Feb	10	11	14	15	12	17	19
Mar	21	29	32	35	29	36	45
Apr	35	48	62	72	52	75	91
May	103	126	140	145	126	144	152
Jun	158	162	165	166	164	166	169
Jul	179	180	181	182	181	181	179
Aug	167	164	158	158	163	158	155
Sep	119	116	115	119	116	120	123

Table S4: Monthly inflow and outflows for the select 13 reservoirs in the study domain under historical (1950-2000) and future projected climate change scenarios (2040-2090, 2 CM-MIROC5 and HadGEM2)

Months	**Historical inflow**	**Historical outflow**	**Projected inflow**	**Projected outflow**	**Surplus baseline***	**Surplus future#**
Oct	0.2	0.3	0.1	0.3	0.2	0.2
Nov	0.2	0.2	0.2	0.3	-0.1	0.1
Dec	0.4	0.2	0.4	0.3	-0.2	-0.1
Jan	0.6	0.3	0.6	0.3	-0.3	-0.3
Feb	0.7	0.3	0.6	0.3	-0.3	-0.3
Mar	0.8	0.7	0.8	0.6	-0.2	-0.3
Apr	1.2	0.9	1.1	0.6	-0.3	-0.5
May	2.0	1.6	1.1	0.9	-0.4	-0.2
Jun	1.7	1.5	0.3	0.8	-0.2	0.4
Jul	0.7	1.2	0.1	0.7	0.5	0.5
Aug	0.3	1.0	0.2	0.5	0.7	0.3
Sep	0.2	0.6	0.3	0.3	0.4	0.1
Total	**8.9**	**8.8**	**5.9**	**5.8**	**1.8**	**1.7**

*Surplus baseline is the difference between historical outflow-inflow taking only the positive difference values in July, August, September and October.
#Surplus projected is the difference between future projected outflow-inflow taking only the positive difference values in June, July, August, September, October and November.

Appendix C: Supplemental Information for Chapter 4

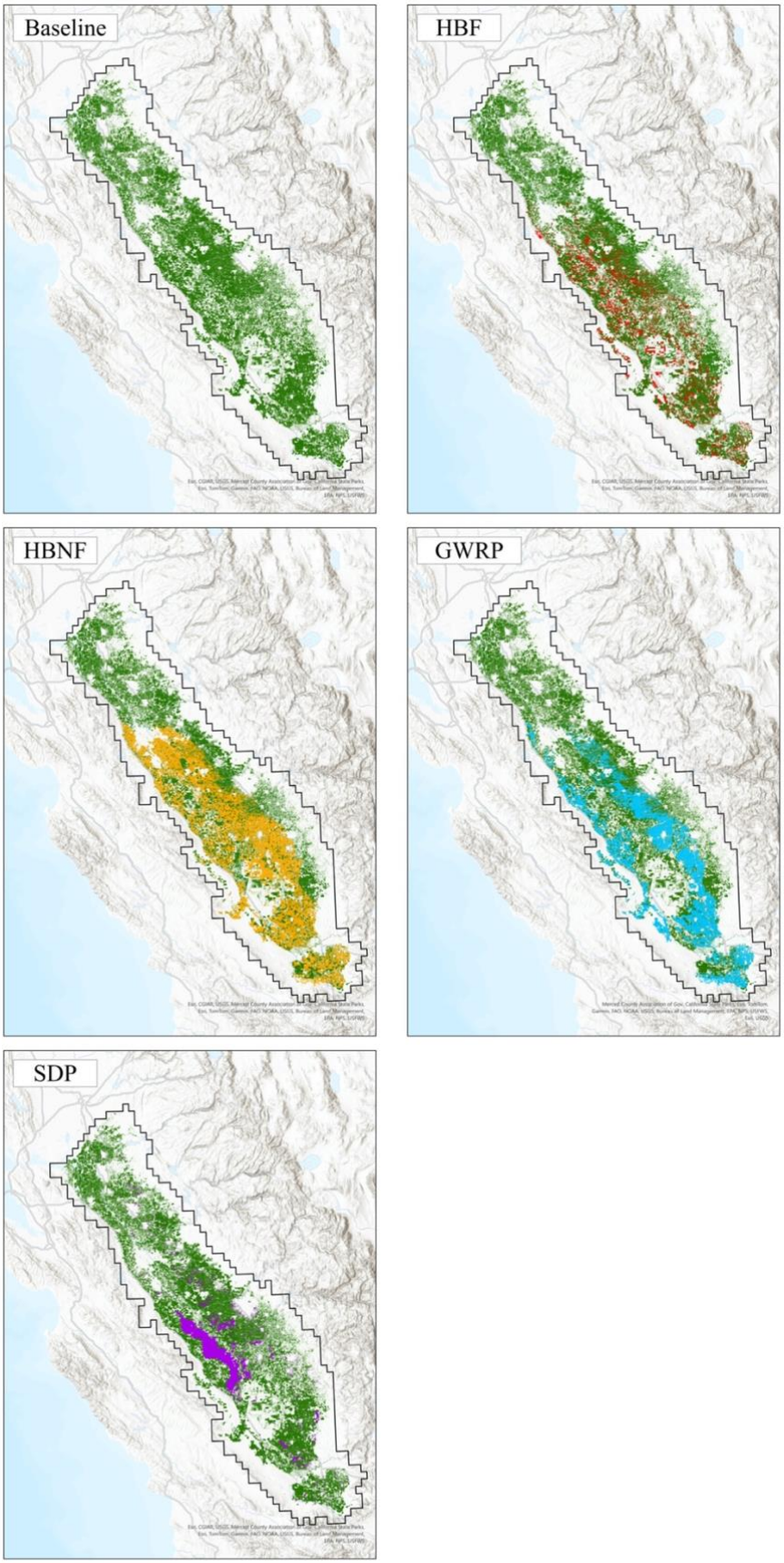
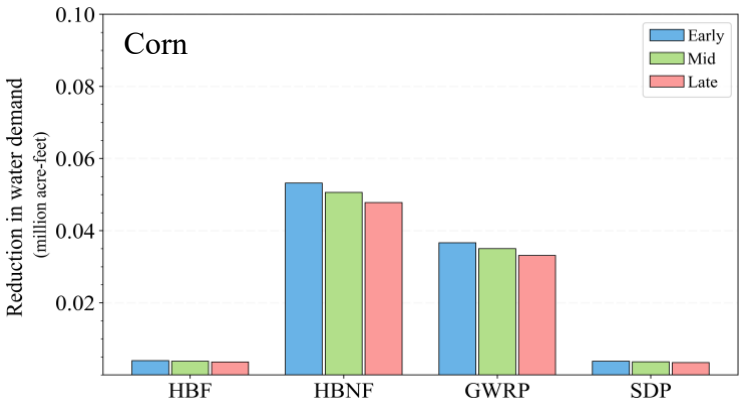
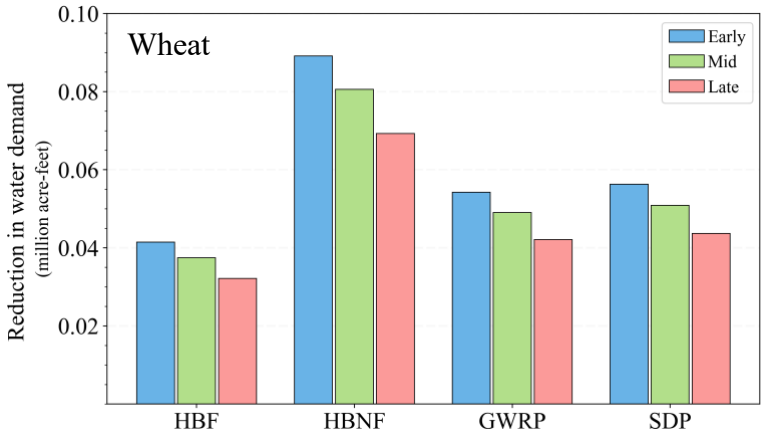
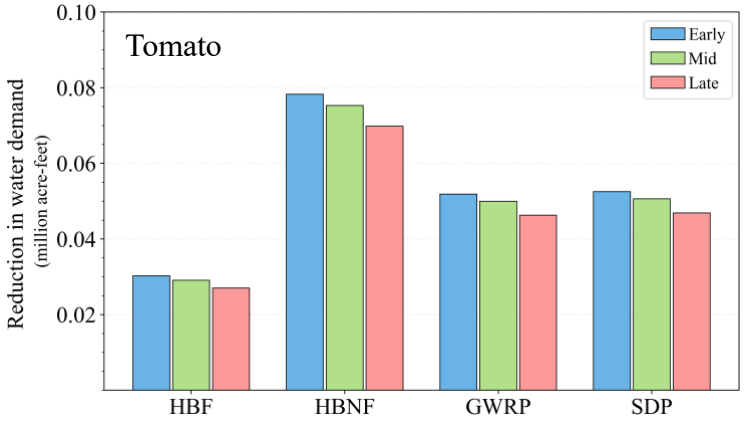


Figure S1: Land use map for baseline and four alternate land use scenarios. HBF: habitat areas with fallowing history, HBNF: habitat areas with no fallowing history, GWRP: suitable habitat sites with good to excellent groundwater recharge potential, and SDP: habitat sites with solar development. potential.


Corn
Early
Mid
Late
Reduction in water demand
(million acre-feet)
0.10
0.08
0.06
0.04
0.02
HBF
HBNF
GWRP
SDP


Wheat
Early
Mid
Late
Reduction in water demand
(million acre-feet)
0.10
0.08
0.06
0.04
0.02
HBF
HBNF
GWRP
SDP


Tomato
Early
Mid
Late
Reduction in water demand
(million acre-feet)
0.10
0.08
0.06
0.04
0.02
HBF
HBNF
GWRP
SDP

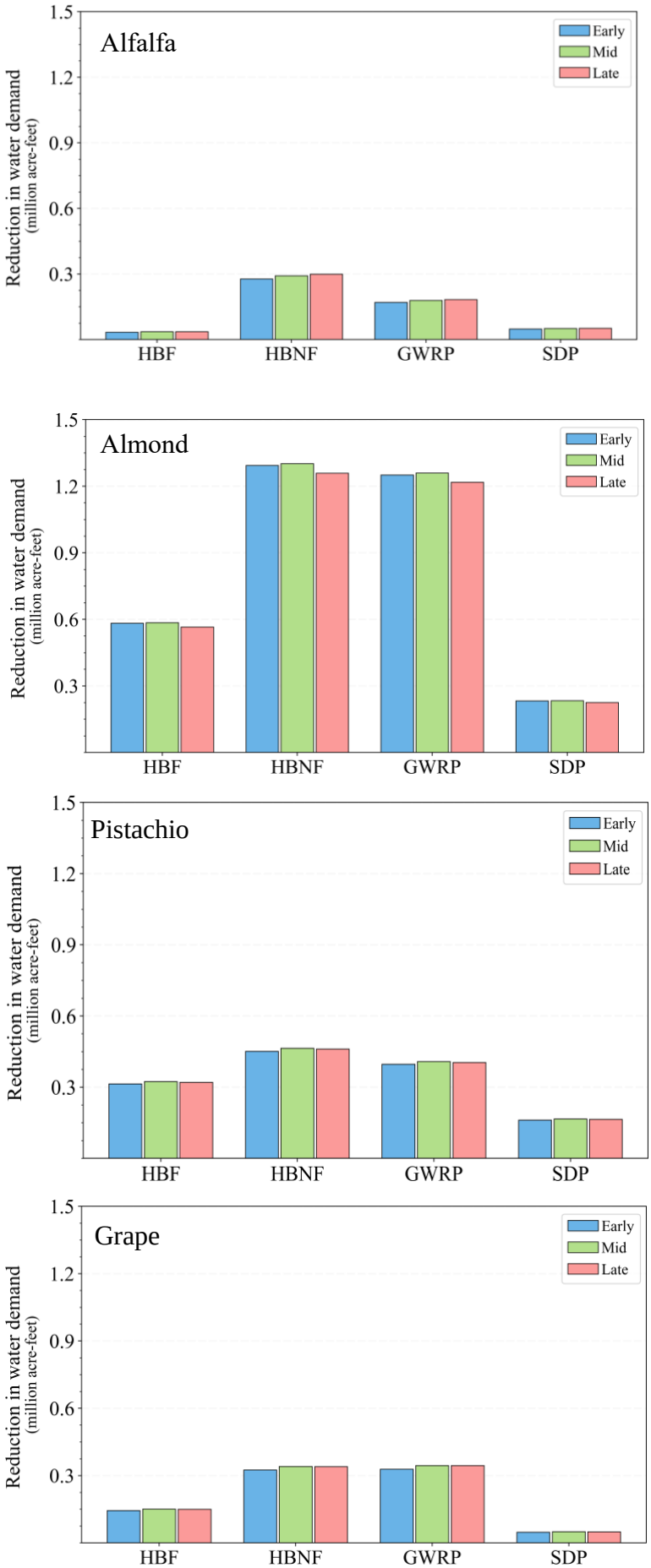


Figure S2: Water demand reduction from the baseline water use by each crop under 4 land use scenarios in early, mid, and late periods of 21st century under RCP 8.5. HBF: habitat areas with fallowing history, HBNF: habitat areas with no fallowing history, GWRP: suitable habitat sites with good to excellent groundwater recharge potential, and SDP: habitat sites with solar development. potential.

Spatial variation in average demand depth under eight land use and climate scenarios in feet/year (mm/year in parentheses)

Scenario	**RCP4.5**	**RCP8.5**
Baseline	0.41 (125)	0.40 (123)
HBF	0.42 (129)	0.42 (129)
HBNF	0.34 (105)	0.34 (105)
GWRP	0.36 (111)	0.36 (111)
SDP	0.41 (125)	0.41 (125)