

**Scales of Sustainable Agricultural Water Management**

By

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*For my mom, Julie*

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## Abstract

Water resources are simultaneously intrinsic to global health and prosperity while being threatened by anthropogenic pressures associated with the population growth that they support. The increase in agricultural production necessitated by the growing population strains water resources that are already exploited and increasingly threatened by climate variability. In this context, there is a need to manage agroecosystems for robustness - the ability to maintain consistency during environmental stress - and resilience - the ability to recover in response to environmental stress. Robust and resilient agroecosystems require sustainable agricultural water management strategies and practices that conserve resources, focus on adaptations to use water more efficiently, and aim to maintain production while reducing adverse environmental impacts. This dissertation uses California as a case of study to explore sustainable agricultural water management from the demand-side. Each chapter uniquely contributes to the understanding of demand-side management strategies, each exploring a different scale with interdisciplinary techniques, to provide practical information for farmers and policy makers. Chapter 1 quantifies the agro-hydrologic impact of winter cover cropping on soil moisture and evapotranspiration on commercial production fields. Chapter 2 models the economic impacts of winter cover cropping in rotation with processing tomato and almond production. Chapter 3 explores the relationship between farmer characteristics and their participation in groundwater management. Results demonstrate how sustainable agriculture practices that improve soil health and sequester carbon can be adopted by specialty crop farmers and contribute to a more robust and resilient future for California agriculture. However, results also indicate that farmers may not have the flexibility to adopt such practices in light of the governance paradox emerging from new groundwater management legislation that does not adequately address the needs of groundwater-dependent farmers. Overall, this dissertation contributes to a coupled understanding of human and environmental systems to ensure the viability of farming, the ecosystems it depends on, and the economies and communities it supports.

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## Introduction

Water is unparalleled by any other resource for its ability to sustain human health, food security, ecosystem services, and economic prosperity. At the same time, the world's water resources are under mounting and unprecedented pressures that threaten global ecosystem and societal functions, including the ability of humanity to feed itself [IPCC, 2014]. Agricultural production is one of the many human systems threatened by freshwater deficits and faces unique water supply, demand, quality, and management challenges as the global climate changes and population grows [Jury and Vaux, 2005]. The futures of both water resources management and agricultural production are uncertain and intrinsically intertwined.

Water supplies and the agriculture they support are threatened by anthropogenic pressures that contribute to climate variability, including population growth, urbanization, and rising consumption [O'dorico et al., 2018, Immerzeel et al., 2020, Gosling and Arnell, 2016]. While scientists have known the global warming effect of  $CO_2$  for over 150 years [Foote, 1856], mitigation efforts are still minimal. Greenhouse gas emissions from human activities, including agriculture, have already negatively impacted water resources through increases in global temperatures and irreversible destruction of land and ocean ecosystems [IPCC, 2019]. As the climate changes, growing populations simultaneously increase demands on the agricultural system. The combined effects of these changes stress food production to a new extreme that leads to increased water demand by an industry that already accounts for 80% of global water consumption, with as much as 10% of the world's food being grown with groundwater from over pumped aquifers [Postel, 2010].

With increased climate variability and the associated changes in water resources availability, there is a recognition that agroecosystems must be managed for robustness - the ability to maintain consistency during an environmental stress - and resilience - the ability to recover in response to an environmental stress. Robust and resilient agroecosystems require **sustainable agricultural water management strategies and practices** that conserve resources, focus on adaptations to

use water more efficiently, and aim to maintain production while reducing negative environmental impacts [Carlisle, 2016]. Such strategies and practices should be developed with an interdisciplinary and holistic approach and then implemented to ensure the current and future viability of farming, the ecosystems it depends on, and economies and communities it supports [Foley et al., 2011]. Sustainable agricultural water management as defined here is a holistic process, not an end point [Childers et al., 2014], that requires a coupled understanding of human and natural systems at several scales.

California is an ideal place to develop this coupled understanding, as a state with immense agricultural production amidst persistent water scarcity. Since irrigated agricultural production began in the 1930s, California has become a primary producer of specialty crops for the entire U.S. and the world. California produces over a third of the country's vegetables, two-thirds of the country's fruits and nuts, and has 9 of the top 10 producing counties in the United States [California Department of Food and Agriculture., 2018a]. To maintain this level of production in a Mediterranean climate, California farmers irrigate an average 2.9 acre-feet (AF) per acre compared to the national average of 1.5 AF [USDA, 2019]. Their irrigation water comes from a combination of surface water deliveries based on a complex water rights structure and groundwater pumping that has been largely unregulated until recently [Hanak et al., 2019]. These water supplies are reliant on snowpack and subsequent spring snowmelt and runoff, whose timing and volume are no longer as predictable due to climate variability and changes [Pathak et al., 2018]. During the most recent drought from 2012-2017, the state's water supplies became stressed to a new level, which highlighted the importance of agricultural adaptation measures that are both robust and resilient. As water supplies become less reliable and more expensive to access and use in California, the hydrologic impacts of sustainable agriculture become a critical component of grower decision making.

California faces an uncertain water future where conservation must become a way of life through demand-side water management. This entails finding ways to reduce irrigation requirements, rather than augmenting water supplies, and storing water underground as soil moisture, rather than in traditional infrastructure, such as reservoirs. Historically, demand-side management has not been a primary strategy used in California agriculture but has been a viable adaptation option to respond

to water scarcity in other Mediterranean climates [White and Fane, 2002] and will be necessary for California’s agricultural community to adapt to reductions in water supplies that cannot be augmented using traditional techniques [Hanak et al., 2019]. In this context, my research question is:

*How can farmers maintain food production under a changing climate while reducing their water use?*

To answer this question, the goal of this dissertation is to bridge hydrologic, agronomic, and social sciences to study multiple scales of sustainable agricultural water management from the demand-side, which focuses on water-users to reduce pressure on water supply systems. In this context, this work explore sustainable agricultural water management strategies from an **infrequently-used perspective**, demand-side management, **various spatial scales**, from an inch of irrigation water to statewide water policy, and using **interdisciplinary techniques**, including micro-meteorological methods, economic modeling, and stakeholder feedback collection (Figure 0.1).

This dissertation includes three chapters that address specific research goals at progressively broader scales of demand-side water management. The chapters are designed to stand alone and therefore each contains its own abstract, introduction, methods, results, discussion, and conclusions. The first two chapters explore the agro-hydrologic and economic feasibility of adopting soil conservation practices in California, followed by the third chapter that looks at the role of farmer participation in state-wide groundwater management policy.

Chapter 1 explores **ecological sustainability at the field scale**, specifically the agro-hydrologic impact of winter cover cropping. This chapter addresses the reality that agricultural water management begins with soil management. Winter cover cropping is one such soil management practice that may improve agricultural field conditions so that water is used more efficiently, but more information is needed on the extent of this ecosystem service [Blanco-Canqui et al., 2015]. There is a particularly need to address this knowledge gap in California, where the price of irrigation water is increasing while its use is being increasingly monitored, and adoption of winter cover cropping maybe hindered by a lack of understanding of the associated hydrologic impacts [Carlisle, 2016]. By quantifying the agro-hydrologic impacts of winter cover cropping on commercial farms, this first chapter contributes to understanding the trade-offs between their associated ecosystem services (i.e.

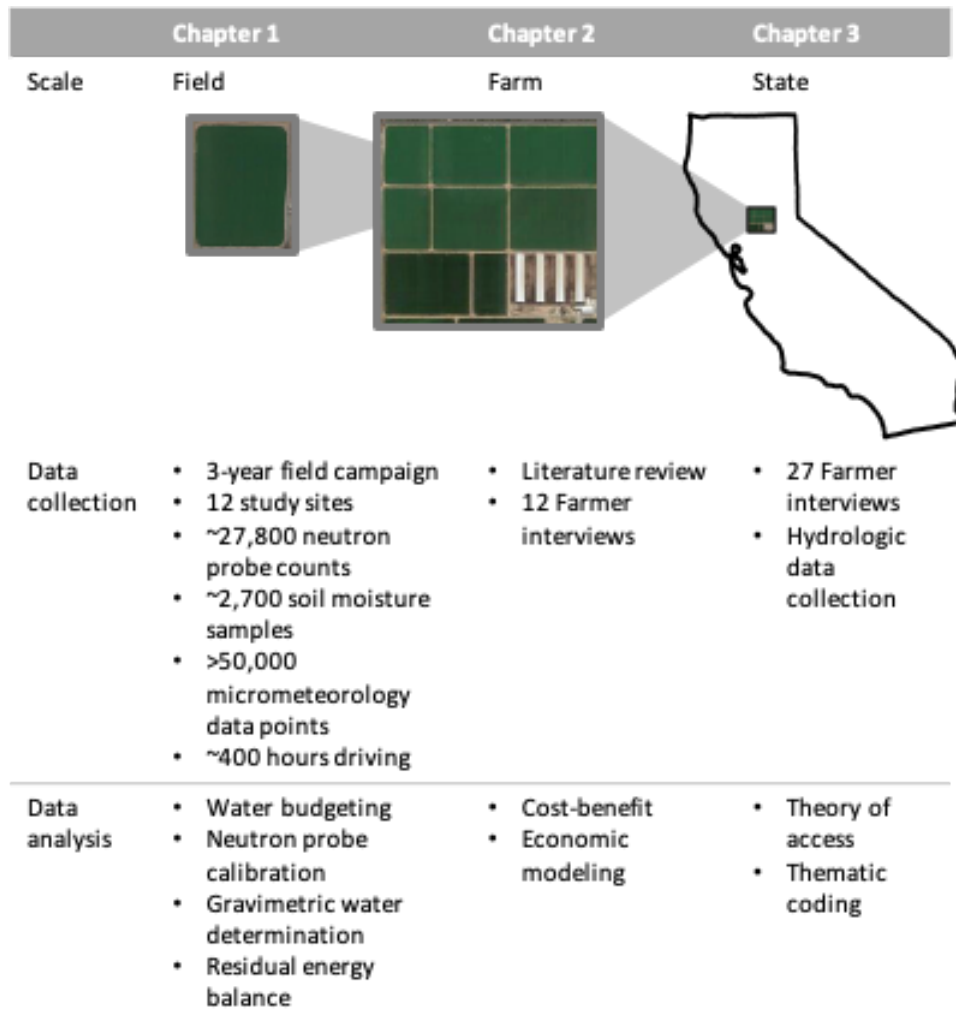


FIGURE 0.1. Dissertation schematic.

biomass production, carbon sequestration, erosion control) and the consumptive water use of the commercial production crops being grown [Rodriguez et al., 2009].

Chapter 2 explores **financial sustainability at the farm scale**, specifically the economic viability of winter cover cropping. This chapter addresses the reality that financial sustainability is a critical component of sustainability [Sze, 2018]. Farmers are more likely to adopt practices they perceive as profitable and there is a need for research on the long-term financial impacts resulting from the adoption of best management practices [Prokopy et al., 2008], including cover crops and their level of return across the U.S. [Bergtold et al., 2017, Blanco-Canqui et al., 2015]. For California specialty crop growers, who manage heterogeneous operations with unique managerial

needs, the economic impacts of winter cover cropping are uncertain and may be another barrier to adoption. This second chapter contributes to this knowledge gap by monetizing both direct and indirect costs and benefits associated with winter cover cropping and modeling their economic viability in scenarios of water, climate, and policy changes.

Chapter 3 explores **policy sustainability at the state scale**, specifically how farmer characteristics impact their participation in state-wide groundwater management processes. Farmer involvement in groundwater management processes at the institutional level is both imperative [**for Economic Co-operation and Development, 2008**] and under-studied. This chapter addresses knowledge gaps in both water management and agricultural adaptation research, including understanding local water management efforts and their corresponding conflict and/or cooperation in the past 15 years [**Bernauer and Böhmelt, 2020**], and the role of social factors (e.g. actors, networks) in facilitating systemic change in agriculture [**Davidson, 2016**]. The last chapter contextualizes farmer interviews with environmental data to inform the ongoing, local implementation of groundwater management legislation.

The unique combination of methods used in these three chapters is at the heart of both the novelty and the limitations of this research. The combination provides a holistic perspective on agricultural water management that would be impossible to achieve working at any individual scale or with skills from any one discipline. However, it also required reconciling conflicting assumptions and expectations inherent to interdisciplinary efforts. The dissertation ends with a discussion of these limitations and outcomes, as well as an outline for future inquiry. Results from this dissertation will provide information to support decisions by farmers, water managers, and policy makers in California and across the arid Western U.S.

## CHAPTER 1

# Agro-hydrologic impacts of winter cover cropping in California's specialty crop fields may be minimal

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### 1.1. Abstract

As fresh water supplies become more unreliable, variable, and expensive, the water-related implications of sustainable agriculture practices are drawing increasing attention from California's agricultural communities. The adoption of winter cover cropping remains limited among specialty crop growers who face uncertainty regarding the agro-hydrologic effects of this practice, such as the water required to establish and maintain a cover crop or possible changes to soil moisture, which could lead to changes in irrigation requirements. This article reports findings from a research study aimed at investigating how winter cover crops affect soil water and evapotranspiration on farm fields that span climatic and farming conditions of California's Central Valley. We collected comparative measurements in cover-cropped and control plots during winter months in three systems: processing tomato fields with cover crop, almond orchards with cover crop, and almond orchards with native vegetation. Our results suggest that winter cover crops in California's Central Valley may break even in terms of actual consumptive water use. Generally, there were not significant differences in soil moisture between cover-cropped and clean-cultivated fields throughout or at the end of the winter seasons from 2016-2019, while evapo-transpirative losses due to winter cover crops were negligible relative to clean-cultivated soil. California growers of high-value specialty crops in the Central Valley can likely adopt winter cover cropping without altering their irrigation plans and management practices.



## 1.2. Introduction

Water usage for agricultural production has become a focus of attention, as the combination of climate change and population growth threaten freshwater resources [IPCC, 2014]. For irrigated agriculture to be sustainable, land use decisions must consider water as a limiting factor, however empirical data on water implications for many sustainable agricultural practices are lacking [Iglesias and Garrote, 2015, Rodriguez et al., 2009]. The lack of such information can lead to low adoption of sustainable agricultural practices such as winter cover crops in California [Carlisle, 2016]. Given both the increase in variability and demand for water in California's Central Valley, farmers in this region may not adopt winter cover cropping, despite its documented benefits, due to uncertainties around the water required to establish and maintain a cover crop during dry winters, the possible changes to soil moisture and spring-summer irrigation requirements, and inter-annual variability of water supply. Empirical evidence is needed to address these water-related uncertainties and inform potential adopters of agricultural practices meant to conserve resources and build healthy soils.

Despite the fact that winter cover crops have emerged as a sustainable agricultural management practice, they are not yet commonly adopted in the semi-arid Western states and are grown on less than 5% of farmland in California [Soil Health Institute, 2019]. Winter cover crops grow in the cool season between specialty crop production cycles - when the land would otherwise be left fallow - and offer extensive soil-related benefits that can create the conditions for resource-efficient agriculture in many climates and production systems [Lu et al., 2000, Pieters and McKee, 1938, Shackelford et al., 2019, Keating et al., 2010, Delpuech and Metay, 2018]. Winter cover crops refer to a wide variety of plants including native grasses or seed mixes of annual grasses and legumes. A grower's choice of winter cover crop type will depend on the specific needs, logistics, and management of their crop system and operation.

California growers produce a majority of the fruits and nuts consumed in the U.S., including processing tomatoes and almonds, amidst a combination of pressures that affect their management decisions [California Department of Food and Agriculture., 2018a]. Growers must manage water resources to meet the unique agronomic requirements of their crops within a highly engineered system of surface water deliveries, while complying with environmental regulations, and under a

changing climate that is creating increasingly variable and often unreliable water supplies [**Hanak et al., 2019, Aguilera et al., 2013, Pathak et al., 2018**]. Pending implementation of the Sustainable Groundwater Management Act may result in the creation of water markets or pumping restrictions, compounding grower uncertainties around water availability from changes in timing and volume of spring snowmelt runoff. To compound the situation, major institutions responsible for designing and implementing agricultural management policies may push farmer priorities in opposing directions.

As water supplies become less reliable and more expensive to access and use in the Central Valley of California, the water-related implications of sustainable farming practices become a critical component of grower decision making. Past research suggests that cover crops may deplete soil moisture and calls for a more comprehensive analysis of the agro-hydrologic implications of winter cover cropping in California’s specialty crop industries [**Mitchell et al., 2015, Mitchell et al., 1999**]. This research is often dated or has been conducted in temperate regions of the United States (U.S.) not facing similar agricultural challenges as California [**McVay et al., 1989, Prichard et al., 1989**], highlighting a knowledge gap in understanding the soil water dynamics and budget. While growers anticipate benefits from winter cover cropping, they lack concrete information to decide if the potential water footprint is worth the operational costs and potential hurdles associated with this practice [**DeVincentis et al., 2020, Sarrantonio and Gallandt, 2003**]. This paper builds off these previous works to conduct specialty-crop specific research using current data collection methods and analytical tools to inform farms of the water-related effects of winter cover cropping across the state’s ecoregions.

Farmer needs and a knowledge gap motivate the main research question of this study: what are the agro-hydrologic effects of winter cover cropping on agricultural production fields across specialty cropping systems and climate gradients in California? The answer is critical to understanding the water-related implications of winter cover cropping and barriers to adoption of this sustainable farming practice in semi-arid irrigated systems. We monitored comparative plots of winter cover crop and bare ground to quantify changes in soil moisture and evaporation. Our findings may have implications for growers, water resource planners and managers, and policy makers working

at the interface of agricultural production and resource conservation in the water-limited context of California and other western U.S. states.

### 1.3. Methods

Winter cover crops may affect the water balance on farms in the short-term through improved rainfall capture and infiltration, changes in evapotranspiration, dew capture, and soil cooling, or in the long-term through increased organic matter content that improves soil-water dynamics [Lu et al., 2000, Tautges et al., 2019, Basche et al., 2016]. The aim of this research was to assess how winter cover crops affect two components of the water budget, i.e. soil moisture and field evapotranspiration, during the period from late Fall to early Spring, on irrigated tomato and almond production fields in California’s Central Valley. Comparative plots of winter cover crops and bare ground (clean-cultivated soil), serving as control, were established to quantify these parameters in the two crop systems across California’s broad climate gradient. Specifically, our research team first analyzed the soil water content using soil moisture measurements, and then determined water losses due to actual evapotranspiration ( $ET_a$ ) using the residual of the energy balance (REB) method. The resulting datasets were then analyzed and interpreted to identify agro-hydrologic effects by comparing soil water content and water losses between cover-cropped and control plots at each study site (Figure 1.1).

**1.3.1. Experimental design.** The study was conducted over a three-year field campaign on commercial production farms and research sites throughout the Central Valley. Ten field sites were established through partnerships with eight commercial farms and two experimental facilities located at University of California Agricultural Experimental Stations to represent the diversity of operations within the Central Valley (Figure 1.2). Variables differing among sites included: annual precipitation, average temperature, past use of winter cover crops, soil type and management history, and whether it was an annual (tomato) or perennial (almond) cropping system. The selected study sites manage three types of winter cover crop systems: 1) cover crop planted in fields where processing tomatoes are grown in rotation with other annual crops, referred hereafter as annual rotation fields; 2) cover crop planted in the tree inter-rows of almond orchards, and

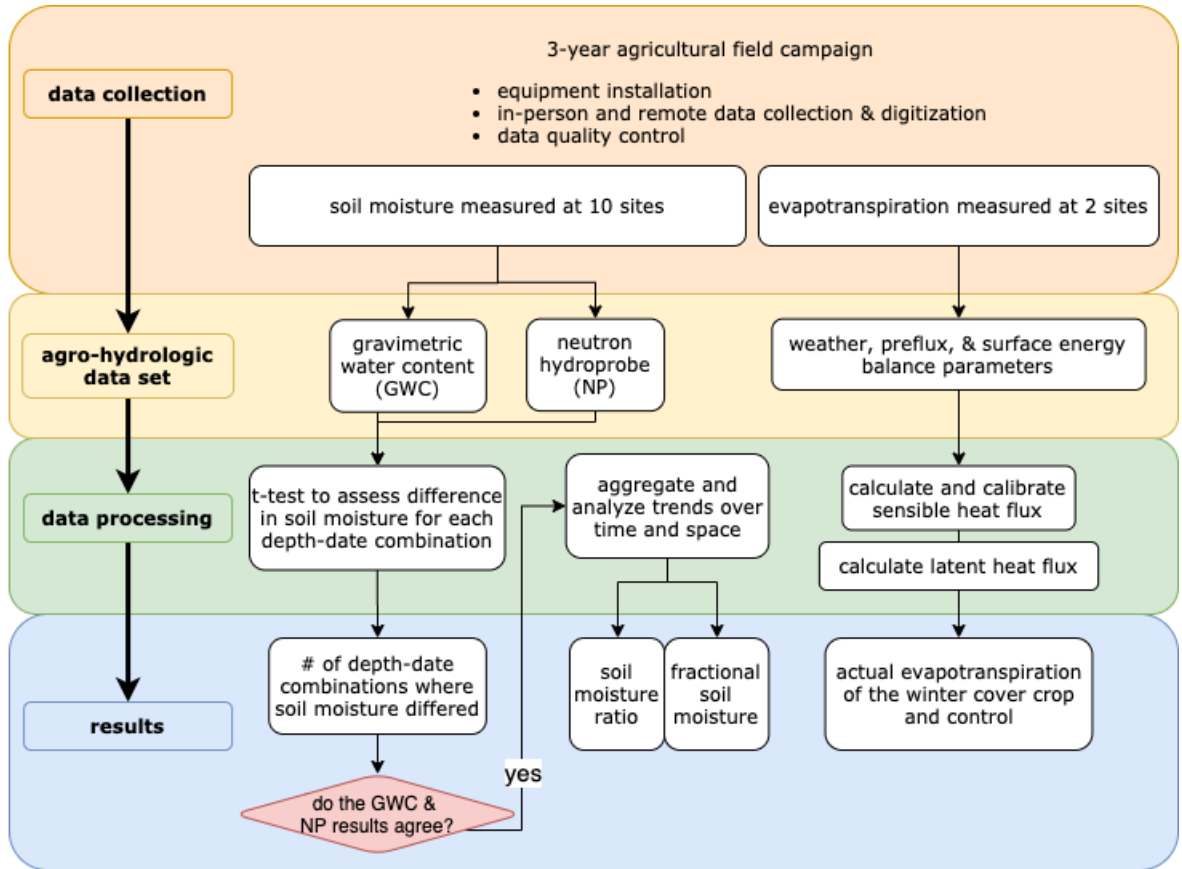


FIGURE 1.1. Flow chart of experimental design for chapter 1.

3) native vegetation allowed to grow in tree inter-rows in almond orchards, which represents the simplest orchard floor management practice

A replicable experimental design was implemented at each study site while working within the grower's capacity and means to accommodate the data collection process. On-farm experimental design included a cover-cropped area to be compared with a control area (clean-cultivated) of at least four acres in the annual rotation fields, and at least of four rows in the almond orchards. Vegetative growth in the control areas was suppressed with herbicide application at most sites.

**1.3.2. Data collection.** The soil moisture data collection process generally started in late Fall and continued until early Spring for the annual rotation fields, and early Summer for almond orchards from 2016 to 2019. Soil moisture was measured consistently using a neutron hydroprobe and gravimetric soil moisture determination from soil samples, although measurement frequency

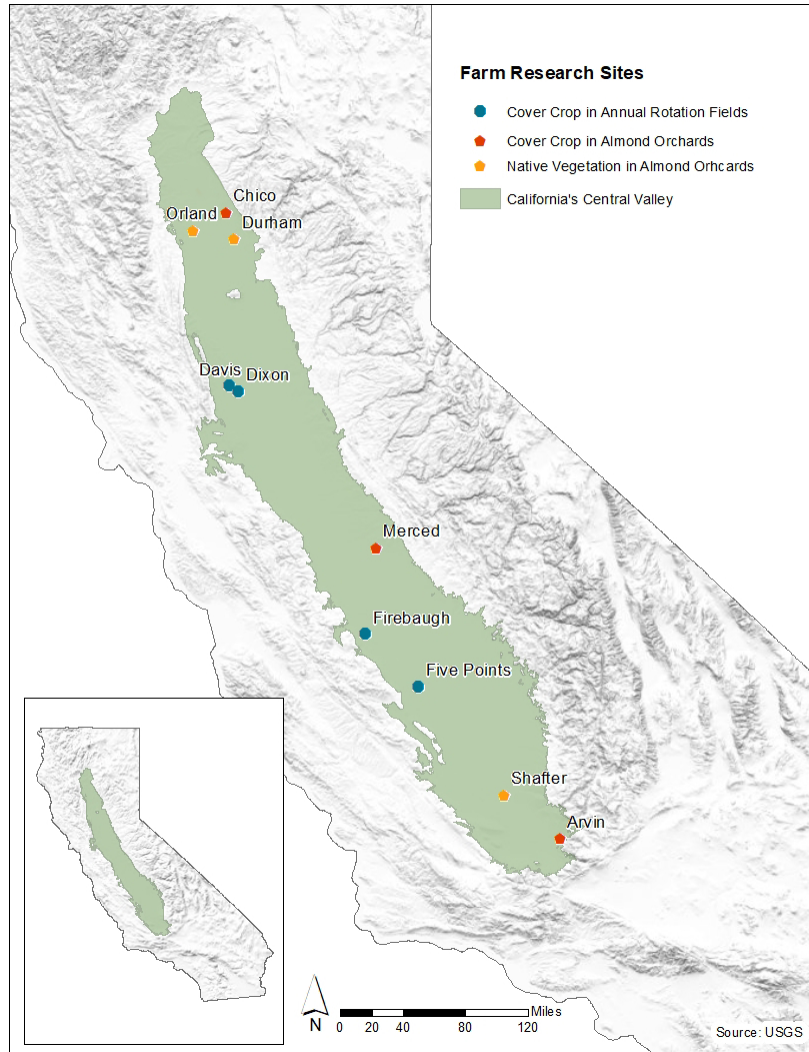


FIGURE 1.2. Map of data collection sites that includes eight commercial production farms and two University of California research farms.

varied between sites. The  $ET_a$  of the cover-cropped and clean-cultivated plots was determined for two sites (Davis and Five Points) from 2017-2018 with the residual energy balance (REB) method using the surface renewal (SR) technique and equipment.

1.3.2.1. *Soil moisture.* Seasonal changes in soil moisture between cover-cropped and control areas were measured at all sites using a neutron hydroprobe (Campbell Pacific Nuclear, Martinez, California) with replications in time to varying degrees. A minimum of four neutron hydroprobe access tubes were installed in each treatment area at each study site to enable soil moisture readings between 0.15 m below the soil surface and 2.7 m deep at 0.30 m increments, if site conditions

permitted. Neutron hydroprobes measure soil moisture based on emissions of ‘fast’ neutrons by a radioactive source through radioactive decay. The neutrons collide with atoms in surrounding soil and a detector measures the quantity of low-energy neutrons that is lost energy through collision with hydrogen. The result is a count rate of slowed neutrons that is proportional to the density of hydrogen atoms near the radioactive source, which provides a proxy for soil moisture.

Analytical determinations of the gravimetric water content were conducted on 2,755 soil samples to validate results from the neutron hydroprobe readings. The soil samples were taken during the installation of the neutron probe access tubes and sporadically throughout the field campaign [Grismer et al., 1995]. Sampling events were collected at 0.15, 0.30, 0.60, 0.90, and 1.2 m using a 75 mm auger when site conditions permitted. Gravimetric water content (GWC, g water/ g soil), which describes mass of water per mass of dry soil, was calculated using a soil sample’s wet and dry weights based on Equation 1. The sample’s wet weight was measured on site after samples were packaged in metal tins. The sample’s dry weight was measured in the laboratory after drying at 110 degrees Celsius for a minimum of 72 hours or when the soil sample reached constant weight.

$$Equation1 : GWC = \frac{\text{wet weight of soil (g)} - \text{dry weight of soil (g)}}{\text{dry weight of soil (g)}}$$

1.3.2.2. *Evapotranspiration.* The  $ET_a$  was measured in cover-cropped and clean-cultivated plots for two consecutive winter seasons (2017 and 2018) at two study sides (Davis and Five Points) with the REB method. The REB method calculates the latent heat flux (LE) as the residual of the surface energy balance, which is then used to determine  $ET_a$ . LE is calculated from data collected with research-scale micro-meteorological measurements of net radiation, sensible heat flux and ground heat flux, which are main parameters of the surface energy balance. Micro-meteorological measurements are among the most direct and viable approaches to obtain information of actual water use by an area of interest. They are also more beneficial over point measurements (i.e. lysimeters, soil moisture, plant water status, etc.) because they provide information over a larger observed study area.

$ET_a$  of the cover-cropped and clean-cultivated plots was determined according to Equation 2 where LE is the latent heat flux ( $MJd^{-1}m^{-2}$ ),  $R_n$  is net radiation ( $MJ d^{-1}m^{-2}$ ), G is soil heat flux density( $MJ d^{-1}m^{-2}$ ) and H is sensible heat flux ( $MJ d^{-1}m^{-2}$ ). Once LE was determined,  $ET_a$

was then calculated using Equation 3 where the coefficient  $\lambda = 2.45 \text{ MJ kg}^{-1}$  and corresponds to the amount of energy necessary to vaporize 1 mm of water from a  $1.0 \text{ m}^2$  surface area [Allen et al., 1998].  $ET_a$  rates obtained from Equation 3 in  $\text{kg d}^{-1}\text{m}^{-2}$  are equivalent to  $\text{mm d}^{-1}$ .

$$\text{Equation2 : } LE = R_n - G - H$$

$$\text{Equation3 : } ET_a = \frac{LE}{\lambda}$$

In the present field study, measurements of the surface energy balance parameters were collected using Medium Lite Flux stations consisting of: (a) a net radiometer (NRLite2, Kipp and Zonen Inc., Delft, The Netherlands) to measure  $R_n$  approximately 2 m above the maximum cover crop's canopy height; (b) two  $76.2\text{-}\mu\text{m}$  diameter Chromel-Constantan thermocouples (model FW3 from Campbell Scientific, Logan, UT, USA), both mounted approximately 1.3 m above the cover crop's canopy to measure H at 10 Hz frequency with the SR methodology; (c) two soil sensor packages to calculate G, each consisting of a soil heat flux plate (HFT3, REBS, Bellevue, WA, USA) and two averaging soil temperature thermocouple probes (Tcav, Campbell Scientific Inc., Logan, UT, USA).

For each soil sensor package, the ground heat flux plate sensors were installed horizontally at 0.05 m below the surface, whereas the probes of the Tcav sensor were installed at an angle from 0.04 to 0.01 m depth below the ground surface and were distributed on both sides of the HFT3 sensor in a line perpendicular to the inter-rows of the future tomato plants' rows. One of the G packages was installed in the row and the second G package was located half a way between the plant row and the first soil package. The ground heat flux at the soil surface was estimated using a continuity equation using the mean HFT3 measurements and the change in temperature of from 0.04 to 0.01 m [De Vries, 1963].

All of the above-ground individual sensors were mounted on a structure consisting of two metal fencing posts, driven approximately 1 m into the ground, connected with a metal cross arm. The height of the mounting structure was approximately 1 m above the ground and power for all sensors was provided by a 40-w solar collector panel connected with a 100 A battery for storage. The micro-meteorological data were collected, stored and processed with a CR1000 data logger (Campbell Scientific, Logan, UT, USA). During the last two weeks of data collection, prior to termination of

the winter cover crop, the research team installed three-dimensional (3-d) sonic anemometers (RE, RM Young Inc., Traverse City, MI, USA) at both the cover-cropped and clean-cultivated plots to collect parallel measurements of the sensible heat flux density ( $H$ ) with the eddy covariance (EC) and SR methodologies.

**1.3.3. Data processing.** The substantial set of experimental data provided an opportunity to estimate the effects of cover cropping on soil moisture and  $ET_a$  despite its inconsistencies in time and space, which were due to inherent challenges faced in a field research study covering a large geographic area and involving dozens of on- and off-farm collaborators. The field dataset was analyzed to describe the agro-hydrologic effects of winter cover cropping on agricultural fields across the selected crop systems and various climatic conditions.

1.3.3.1. *Soil moisture.* To determine how winter cover crops affected soil moisture during the winter season, researchers first digitized all soil water content datasets by transferring data from field notebooks to .csv files. Data were entered manually, and quality controlled by having every neutron probe count and soil sample weight input and later verified against the paper copy by separate individuals. Data were further cleaned by removing any values that missed human detection and were clearly inaccurate, such as neutron probe counts with 6 or 3 digits. Next, soil moisture datasets were analyzed by looking at 1) statistical differences between soil moisture for each individual day and at each depth of data collection, 2) trends in a study site's soil moisture ratio, and 3) trends in the change of fractional soil moisture over the winter season for each winter cover cropping system.

Datasets were first analyzed to determine the percent of time and depth along the soil profile when soil moisture content differed between winter cover crop and control plots at each study site. This determination was done using two measurement methods: neutron hydroprobe and gravimetric soil moisture. A series of t-tests were conducted using R software package (version 3.6.0) to evaluate the significance of the treatment factor (i.e. winter cover crop vs. control) on soil moisture using all measurements collected on a given day and at a given depth for a particular site. A total of 3,755 tests from the neutron hydroprobe and 323 tests from gravimetric soil determination of soil samples were conducted.

Based on the results from such analysis, the neutron hydroprobe data was used to analyze trends in soil moisture over time. Neutron hydroprobe counts were first aggregated by study site,



day, depth, and treatment. The counts were used to calculate soil moisture ratios by dividing the average neutron hydroprobe count from each depth of the cover-cropped plot by the average count from the corresponding control plot. A soil moisture ratio greater than one indicated relatively more water in the cover-cropped plot compared to the control.

Second, fractional soil moisture was calculated for the top 1.2 m of the soil profile to identify trends in cover crop systems. To calculate fractional soil moisture at each site and each day of data collection, the average neutron hydroprobe count was normalized by the maximum soil moisture measured at the corresponding treatment, site, and season. The maximum soil moisture was determined separately for each treatment to account for potential differences in soil hydraulic properties between the individual plots. This process identified a point of relative saturation, i.e. the day when soil in each treatment plot reached its maximum moisture content and allowed us to see how the soil moisture content in each treatment changed over the season. The resulting dataset of fractional soil moisture was used to compare the percentage of peak soil moisture retained by cover-cropped and control plots at the end of the winter season, providing a method to identify trends in a heterogeneous data set.

1.3.3.2. *Evapotranspiration.* Datasets of the surface energy balance parameters collected using micro-meteorological measurements were analyzed and the REB method was used to quantify the actual water losses ( $ET_a$ ) in cover-cropped and control plots. Three data types were compiled and used for the analyses: weather, preflux, and energy balance data [Pawu et al., 1995, Snyder et al., 1996].

First, data control was conducted for quality check to filter for expected and/or reasonable values, and exclude data corresponding to periods of power/voltage issue and rainfall. Gap-filling was also performed, which entailed linear interpolation for short periods of missing data and a lookup table for intermediate gaps. For more than 8 to 12 hours of missing data or when the missing data could not be reasonably gap-filled with the two previous methods, the corresponding daily values were removed from the series or flagged as not available.

The sensible heat flux values were calculated using the SR technique, which entails high frequency temperature readings, and with the EC technique for the periods when 3-d sonic anemometers were used to measure H in parallel with fine-wire thermocouples. As mentioned previously,

the UC research team used Medium Lite Flux ET stations to measure surface energy balance parameters ( $R_n$ , G, H) over the course of the winter cover crop periods in 2017 and 2018. During the last two weeks of data collection in 2018, 3-d sonic anemometers were also deployed to measure H. Specifically, the data collected with the 3-d sonic anemometers were used to compute H using the EC methodology, while the data collected with the fine-wire thermocouples were used to determine uncalibrated H ( $H'$ ) using the SR technique. The sonic anemometer data was corrected by increasing the magnitude of the H estimate from the RM Young sonic anemometer by 12%, according to [Kochendorfer et al., 2012].

The two sets of measurements enabled the calculation of a calibration factor ( $\alpha$ ) for  $H'$  measured with the fine-wire thermocouples using the SR methodology. The  $H'$  is highly correlated with H, and the  $\alpha$  calibration factor was determined by computing the slope of the least-squares regression of H versus  $H'$  separately for positive and negative  $H'$ . Then, the product of  $\alpha \times H'$  provided an acceptable estimate of the half-hourly 3-d sonic H values. In this way, the research team could use Medium Lite Flux stations over the entire course of the cover crop growth season utilizing only thermocouples and the SR methodology to calculate half-hourly  $H'$  values. The  $H'$  values were then multiplied by the  $\alpha$  factor to back-calculate the calibrated values of H for the entire duration of the data collection periods on both cover-cropped and clean-cultivated plots in 2017 and 2018.

For the periods when the 3-d sonic anemometers were used, the half-hourly LE was computed using Equation 2. The daily LE was then determined by summing the 48 half-hourly values of LE ( $\text{MJ } m^{-2}$ ). For the periods when only Medium Lite Flux stations were used, the daily LE was determined by summing the 48 half-hourly values of LE computed using Equation 2 and replacing H with  $\alpha H'$ . Finally, the daily  $ET_a$  ( $\text{mm } d^{-1}$ ) were computed using Equation 3. Additional information on the surface renewal and sonic anemometer analysis used in this research are fully discussed by Shapland et al. (2012).

To compare  $ET_a$  of cover crop and clean-cultivated fields with reference grass surface, reference evapotranspiration ( $ET_o$ ) values were obtained from the nearest weather stations of the California Irrigation Management Information System network (CIMIS, 1989; <https://cimis.water.ca.gov/>). Data were collected from weather stations No. 6 (Davis, CA) and No. 2 (Five Points, CA).

## 1.4. Results and discussion

Our results provide practical information for agricultural producers in California and reveals the complex and variable nature of research in this context. Growers of processing tomatoes and almonds can likely incorporate winter cover crops into their management practices because when compared to bare ground, they do not alter the soil moisture or evapotranspiration enough to substantially affect spring-summer irrigation plans or other water management decisions, supporting previous research findings on Mediterranean climates [Ward et al., 2012].

**1.4.1. Soil moisture.** We analyzed each site’s soil moisture datasets by soil depth and treatment, for individual days of data collection and over time. Soil moisture was generally not statistically different between cover-cropped and control plots during the winter season ( $p$ -value  $< 0.05$ ) (Table 1.1). Of the 3,785 unique depth-day combinations from the neutron hydroprobe data set, 520 (14%) were statistically different; of the 337 unique combinations from the gravimetric soil water content data set, 39 (12%) were statistically different. The trend of minimal difference in soil moisture from the neutron hydroprobe data set was confirmed with results from the gravimetric soil moisture determination (Figure 1.3), therefore the remainder of analyses were based on the neutron hydroprobe data set that is more extensive and detailed in both time and space.

Different patterns of soil moisture trends were found for each cover cropping system (Figure 1.3). Annual rotation fields with a winter cover crop showed the widest range of soil moisture, with percentage of time when soil water content differed ranging from 2 to 29% with respect to clean-cultivated plots. This high variability may be a function of the specific management history on each field, which differed among the four sites, as well as the soil- and crop-specific agro-hydrologic impacts of winter cover cropping. Almond orchards with winter cover crop showed a more consistent behavior, possibly because almonds are grown on a narrower range of soils than processing tomatoes in California with low to no soil disturbances. The soil moisture at these almond sites was not statistically different between the cover-cropped area and the control over 95% of the time ( $p$ -value  $< 0.05$ ) These sites had the fewest depth-date combinations to analyze (959) and did not grow winter cover crops before the present experiment. Almond orchards that allowed growing native vegetation as a winter cover crop showed differences in soil moisture with

TABLE 1.1. Summary of neutron hydroprobe data collected from 10 research sites. Data was collected to identify trends in soil moisture in cover-cropped and control (bare ground) plots on agricultural fields in California’s Central Valley.

Site location	Latitude	Days of data collection	Depth-date combinations used in analysis	Percentage of depth-date combinations that had more water in either treatment	
				Cover crop	Control
<b>Cover crop in annual rotation fields</b>					
Davis	38.55	47	423	0.2	2.1
Dixon	38.51	32	288	2.8	4.2
Firebaugh	36.73	21	208	18.8	0.5
Five Points	36.34	41	342	3.2	25.4
<b>Cover crop in almond orchards</b>					
Chico	39.8	29	199	0	3
Merced	37.37	45	450	0.9	2
Arvin	35.2	31	310	3.2	1.6
<b>Native vegetation in almond orchards</b>					
Orland	39.67	62	519	0	11.2
Durham	39.61	60	553	0.7	27.8
Shafter	35.53	50	463	6.9	15.1
<b>Average of all sites</b>				3.7	9.3

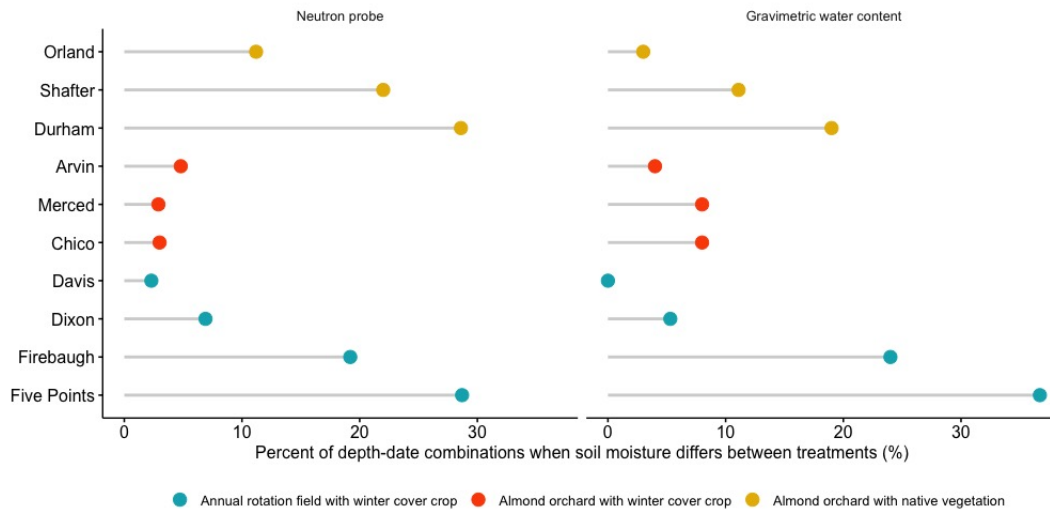


FIGURE 1.3. Percent of observations (depth-date combinations) when soil moisture differs between treatments (cover-cropped and control plots, p-value < 0.05). Values are based on all available data for each site over the entire time period of data collection from 2016 to 2019.

TABLE 1.2. Summary of instances when soil moisture differs between cover-cropped and control (bare ground) agricultural fields in California’s Central Valley.

Winter cover crop system	Percentage of depth-dates where soil moisture differs between treatments	
	0-120 cm	>120 cm
Cover crop in annual rotation fields	93	7
Cover crop in almond orchards	85	15
Native vegetation in almond orchards	78	22
<b>Average of all sites</b>	<b>83</b>	<b>17</b>

a slightly higher frequency, i.e. an average of 20% of the time. There are interesting trends in the instances where soil moisture differed between cover-cropped and control plots. Difference in soil moisture mostly occurred in the cover crop root zone between 0-1.2 m most often, 83% on average across the study sites (Table 1.2). Future studies may only need to look at this part of the soil profile to further investigate the agro-hydrologic impacts of winter cover crops over time.

For almond orchards, the instances when soil moisture differed reveal contrasts between the use of winter cover crop and native vegetation. Orchard plots with winter cover crop show infrequent differences relative to the control plots (Figure 1.3). These sites had not used winter cover crop before the present study and may provide insight into what growers can expect during the transitional period when a farm starts implementing this practice. When native vegetation was used as a winter cover in almond orchards, the soil moisture in the control area is often greater (Figure 1.3). Anecdotally, the present research study documented that during intense winter precipitation events, water pooled on the surface of orchards rows in control plots more than in cover-cropped plots. Pooled water creates unfit farming conditions that could prevent or complicate the use of machinery or trigger the occurrence of anaerobic conditions in almond orchards during the winter. The presence of a winter cover may be reducing compaction and improving infiltration, facilitating vertical and lateral water movement.

A closer look at the individual sites within a single cover crop system reveal important differences between sites that are similar in cover cropping practice, location, and precipitation patterns. The aggregated soil moisture ratios for seasons 1 and 2 show that winter cover crops or native vegetation can impact soil moisture on neighboring production fields in different ways (Figure 1.4. Examining

sites with similar pedoclimatic conditions shows significant differences based on vegetative growth and diversity of cover crop mix. For instance, in the almond orchards the plots with thicker vegetation showed a lower ratio (i.e. more water in the control plot), while in the tomato fields the plots with a mixture of over a dozen seeds showed a higher ratio (i.e. more water in the cover crop plot) than the plots with a three seed mix.

Given the differences between study sites, in particular sites in similar climates and soils, there are not significant differences in soil moisture at the end of the winter season when results from all seasons and sites are aggregated (Figure 1.5). On average, the production fields in this study never lost more than 15% of fractional soil moisture from peak soil moisture by the end of the winter cover crop season, for either winter cover crop or control treatments.

**1.4.2. Evapotranspiration.** Our research team measured actual evapotranspiration ( $ET_a$ ) over the course of two winter cover crop seasons from 2017-2018. The measurements conducted during the first year of data collection provided a proof of concept and allowed the research team to refine the data collection protocols and data management system. This article reports  $ET_a$  values determined from the data collection period of the second year (November 2017 to February 2018), where a ten-fold difference in precipitation between the two sites, Davis (125 mm) and Five Points (12 mm), allow for a climatic comparison from November 15, 2017 to February 20, 2018.

The difference in seasonal cumulative  $ET_a$  between cover-cropped and clean-cultivated ground is negligible in both Davis (3 mm) and Five Points (18 mm) (Figure 1.6). The cumulative  $ET_a$  in Five Points is greater than the amount of precipitation in the same time period, but may have been fed by preceding rainfall and some stored soil moisture, and these differences in consumptive water use can be considered insignificant in the scheme of annual water requirements for processing tomatoes, which are between 450 and 500 mm.

The bi-weekly cumulative  $ET_a$  values in Davis reveal that during periods of abundant precipitation, such as in January 2018, consumptive water losses are actually greater in the clean-cultivated plot and are mainly due to soil evaporation from bare ground. During wet years, it would be advantageous to have a winter cover crop to slightly reduce evapo-transpirative water losses from the top soil layers. In the drier climate in Five Points, the bi-weekly  $ET_a$  from the winter cover crop was always slightly higher than the control, however this measured  $ET_a$  may also include

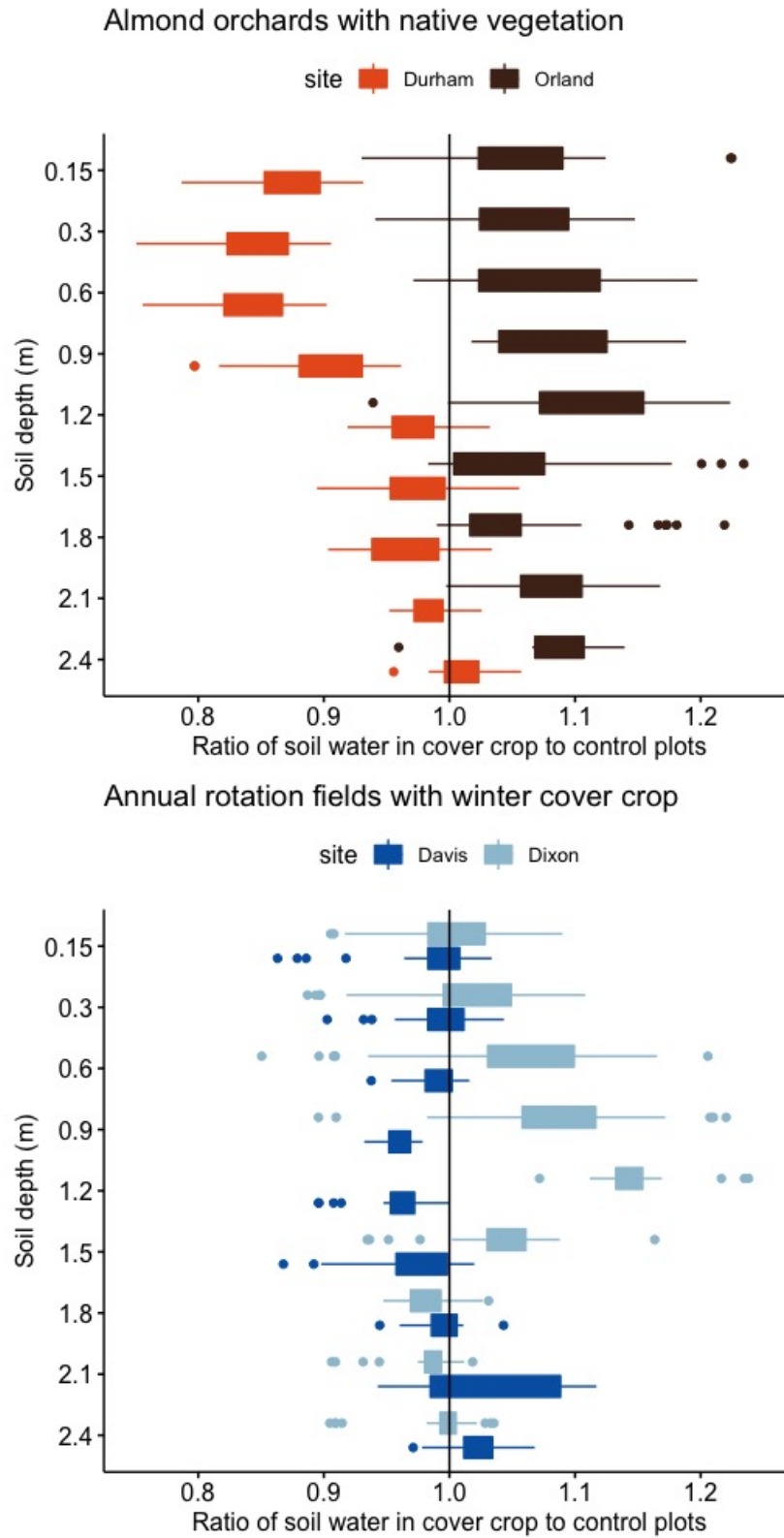


FIGURE 1.4. Ratio of soil moisture content at four study sites based on all available data for each site over the entire time period of data collection for the first two seasons (fall 2016 to spring 2017 and fall 2017 to spring 2018). A ratio greater than one indicates relatively more water in the cover-cropped plot compared to the control.

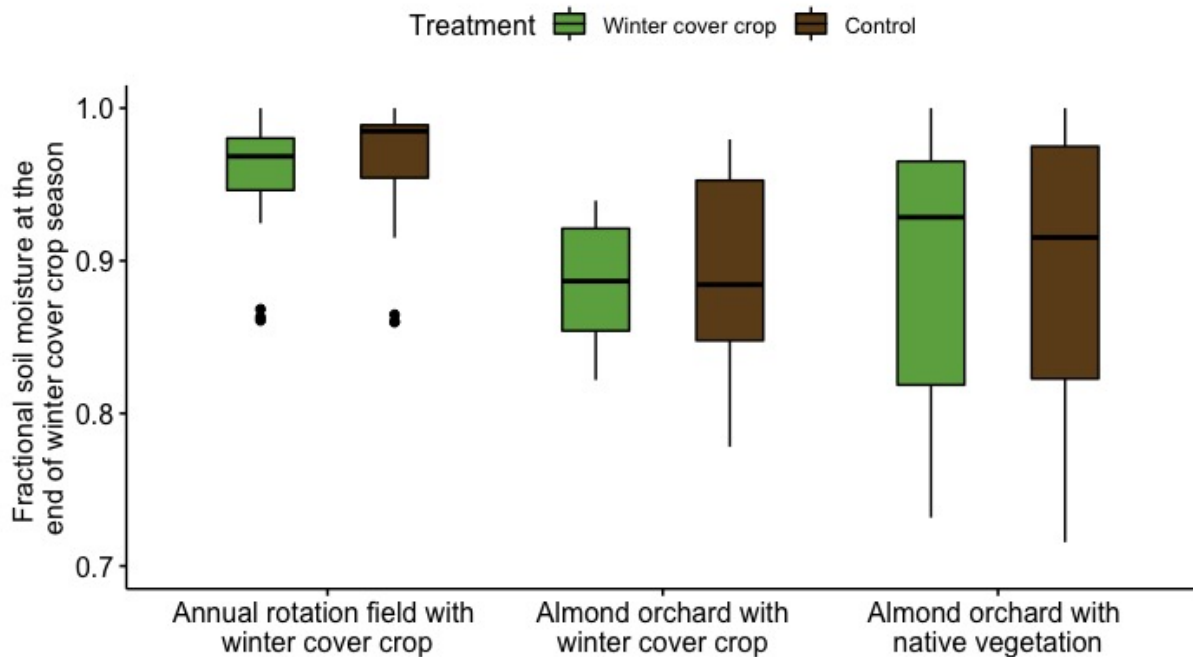


FIGURE 1.5. Box plots of fractional soil moisture averaged across 1.2 m at the end of the winter cover crop season offer a comparison of the percentage of peak soil moisture retained by cover-cropped and control plots.

condensed moisture that the cover crop captured from dew and fog and the cumulative water losses are minimal overall.

**1.4.3. Application and limitations.** The findings from this study may be useful for specialty crop growers in the Central Valley of California for several reasons. Growers with annual fields in rotation with processing tomatoes may experience a variety of changes in soil moisture resulting from winter cover cropping depending on their unique characteristics, such as soil type or management history. Their fields may experience some extra consumptive water losses during dry winters, but the water used by winter cover crops amounts to less than a single irrigation event. This small cost may be offset by the possibility of increased soil moisture after cover cropping for multiple years, which this study did not capture.

Additionally, cover crops can improve the effectiveness of applying water during the dormant season to refill the soil profile and leach salts. These combined potential management implications could incentivize winter cover cropping for specialty growers of annual crops that are concerned



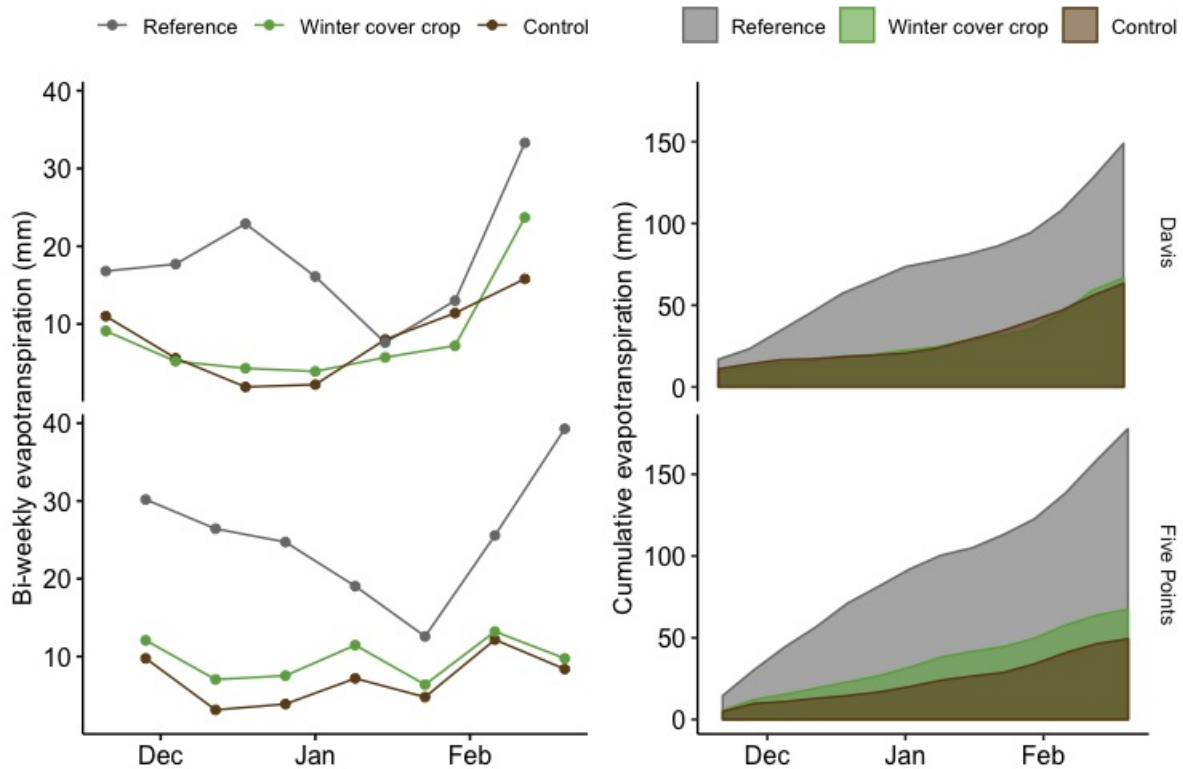


FIGURE 1.6. Bi-weekly and cumulative actual evapotranspiration ( $ET_a$ ) for cover-cropped and control (bare ground) plots on annual rotation fields and reference evapotranspiration ( $ET_o$ ). Data spans a winter cover crop season of data collection from November 2017 to February 2018.

with late winter rains and their implicit harvest complications that can occur rains delay cover crop termination, thereby preventing complicating contractual obligations [DeVincentis et al., 2020].

Almond sites showed slightly more frequent differences in soil moisture due to winter cover, but the interrow cover and almond trees mostly occupy different spatial niches. Growers with young almond orchards can take advantage of the soil health benefits of winter cover crops while their orchards are young without experiencing any major changes in soil moisture due to winter cover cropping. Growers with almond orchards who lease the farmland can allow native vegetation to grow as a winter cover crop to enhance their rhizosphere ecology without incurring costs that may impact their business schemes. However, it is important to note that timing of winter cover crop termination is key to seeing these benefits realized, avoiding delays in normal farming operations, and preventing soil moisture depletion due to extra ET when the temperature increases.

Because the research sites included commercial production fields, these findings are representative of the reality that farmers experience in California. However, the study is limited by the inherent challenges of field-based agricultural research. There are limitations to the extent of control in the experimental design when conducting research on commercial farms. Additionally, our sites differed in management history, years of cover cropping, motivations for growing cover crops, operational resources, type of cover cropping, location, rainfall, timing of cover crop termination, and soil characteristics, just to name a few variables. Collecting data at each of these sites allowed researchers to create a diversified data set with thousands of measurements, but one that required careful analysis in an attempt to appraise the agro-hydrologic aspects for the entirety of the California’s Central Valley.

These limitations can be addressed in future studies that will benefit from the analytical results obtained and the lessons learned during the present field research. Future research efforts aiming to better understanding soil moisture changes that result from winter cover cropping could target only the first meter of soil depth, and at the same time increase the frequency of data collection, including before and after rain events. Such research should look into the rain response impacts of winter cover crops that could be captured with in-situ soil moisture sensors. These sensors do not require the regular site visits that are necessary when using neutron hydroprobes.

Future research efforts to monitor how winter cover crops affect actual field ET are necessary to build on the initial conclusions drawn in this paper. The ET data presented here is limited in its scope of annual rotation fields for two years and future work should aim to produce longer time series of data up to and including the summer months. However, the data we presented in this article are the first of this kind in California and can act as a valuable starting point to build upon with additional and complementary datasets and analyses.

## 1.5. Conclusions

Given the combined agronomic, hydrologic, regulatory, and climatic pressures facing California specialty crop growers, there is a need to identify sustainable agricultural practices that reduce the environmental impacts of farming without complicating other farm management choices. The datasets collected from our study show that there were not significant differences in soil moisture

between cover-cropped and clean-cultivated fields throughout or at the end of the winter seasons from 2016-2019, and that evaporative-losses were minimal. These results suggest that growers can benefit from soil health advantages associated with winter cover cropping without having to change their spring-summer irrigation plans and water management decisions.

## CHAPTER 2

# Using cost benefit analysis to understand adoption of winter cover cropping in California’s specialty crop systems

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### 2.1. Abstract

Winter cover crops could contribute to more sustainable agricultural production and increase resiliency to climate change; however, their adoption remains low in California. This paper seeks to understand barriers to winter cover crop adoption by monetizing their long-term economic and agronomic impacts on farm profitability in two of California’s specialty crop systems: processing tomatoes and almonds. Our modeling effort provides a present, discounted valuation of the long-term use of winter cover crops through a cost-benefit analysis. A net present value model estimates the cumulative economic value of this practice. We then explore how the long-term trade-offs associated with winter cover crops can affect an operation’s profits under a spectrum of hypothetical changes in California’s agricultural landscape. Our analysis sheds light on the barriers to adoption by reporting benefit-cost ratios that indicate profitability across several scenarios; however, benefits and costs accrue differently over time and with long planning horizons. At the same time, a small portion of gained benefits are external to the grower. Findings from this study reveal that winter cover crops in California can be profitable in the long term, but the extent of profit depends on the cropping system, extent of irrigation savings due to improved soil function, access to financial subsidies and climate change. Winter cover crops can return positive net benefits to growers who have flexible contractual obligations, can wait for the long-term return on investment and manage cover crops as closely as cash crops. This analysis contributes to the study of conservation

agriculture practices by explaining possible reasons for low adoption through an economic valuation of the implications of soil management choices and policy counterfactuals.

## 2.2. Introduction

Winter cover cropping is a promising agricultural soil management practice that may contribute to increasing food production while using natural resources more sustainably. Winter cover crops, which are grown on agricultural fields that would otherwise be left fallow, mimic natural landscapes, promote soil microbial diversity, capture solar radiation, cycle nutrients, reduce erosion, mitigate climate change and climate change effects [Aguilera et al., 2013, Blanco-Canqui et al., 2015, Vukicevich et al., 2016]. Widespread adoption of winter cover cropping could contribute to more sustainable agricultural production and increase the resiliency of the agriculture industry to policy and climate changes [Ewel, 1999, Kremen and Merenlender, 2018, Lu et al., 2000]. Despite their well-known soil health benefits, winter cover crop adoption varies significantly across the U.S., with very low adoption rates between the production of specialty crops in California [Soil Health Institute, 2019]. Understanding trends in cover crop adoption requires knowledge of the long-term impacts on farm profitability: how do the benefits and costs of cover crops change with each operation depending on geography, cropping system, management choices, and other economic factors? [Bergtold et al., 2017]. This type of knowledge can address growers' concerns that cover crops impact cash crop performance, establishment, and soil moisture for their specific cropping system [Carlisle, 2016]. Understanding adoption incentives is also critical for informing agri-environmental policy and promoting sustainable agriculture in a changing climate.

Several reasons may explain low rates of winter cover crop adoption in California. First, it may be that the net present value of cover cropping in specialty crops systems is negative and observed adoption rates are a reflection of rational, profit-seeking behavior. Alternatively, it may be that the net present value is positive, but only in the long run. If it takes many years for benefits to accrue to acceptable levels, low adoption rates could then be rationalized by farmers exhibiting myopic behavior. A third explanation comes from the idea that a substantial portion of the benefits may be external to the grower who makes soil management decisions (e.g. improved water quality to a downstream user), and thus low adoption rates reflect the presence of these externalities. Lastly,

the existence of information barriers, risk and uncertainty on behalf of farmers can hinder adoption as well [Ghadim and Pannell, 1999, Klonsky and Livingston, 1994, Prokopy et al., 2008].

This paper conducts a cost-benefit analysis of winter cover cropping for two specialty crops, processing tomatoes and almonds, which are widespread in California’s Central Valley, and provides insight into possible explanations for low adoption. A review of previous studies reveals an emphasis on the benefits and costs of cover cropping in the Midwest and East Coast of the U.S. [Bergtold et al., 2017]. Less well understood are the reasons for low adoption in California or how climate change may modify this ecosystem service [Bai et al., 2019]. Past research on adoption of sustainable practices highlights the need for understanding long-term financial impacts [Lu et al., 2000, Prokopy et al., 2008, Wyland et al., 1996] and specific information on how practices fit into particular farming situations [Rodriguez et al., 2009].

We address this knowledge gap with a model of the economic viability of growing winter cover crops in two crop systems in California’s Central Valley under a spectrum of hypothetical scenarios. The model tests the hypotheses that (1) the benefits of winter cover crops are not captured in an annual analysis, but rather accrue over time to a point of financial return, and (2) the economic profitability of growing winter cover crops will switch in response to changes in climate, water and policy. Further, our model improves on previous methodologies by validating literature estimates through grower interviews and field data collection. We contribute to the literature on conservation and sustainability by exploring policy counterfactuals, monetizing impacts of soil management choices and shedding light on diffusion of environmental innovation [Aldieri et al., 2019]. Results from this research can inform on-farm and policy decisions as producers and regulators strive to maintain sustainable agricultural production under a changing climate.

### 2.3. Methods

Our goal was to comprehensively quantify the costs and benefits associated with winter cover cropping in monetary terms for two of California’s specialty crop systems. The valuation exercise had two purposes. First, it explained how the long-term trade-offs associated with this soil management practice affect an operation’s profits. Second, it tested the economic viability of cover

cropping under a spectrum of hypothetical changes in California’s agricultural production and policy conditions. This research was focused on two specialty crop systems of interest: processing tomato (referred to as tomato) [Turini et al., 2018] and almond [Duncan et al., 2016]. The tomato system was analyzed as part of a typical crop rotation consisting of onions, winter grains, cotton and garlic. Tomatoes and almonds were chosen so that the analysis represented one annual and one perennial system, both of which are leading commodities in California [California Department of Food and Agriculture., 2018b]. We collected data to model these systems with interdisciplinary methods by supplementing a traditional literature review with on-the-ground field research conducted in agricultural production areas of the Central Valley. The methodology is summarized in Figure 2.1 and described in detail below.

**2.3.1. Data collection.** Our study used data from three main sources: estimates from previous literature, semi-structured grower interviews and a field-based experiment. We used these data to estimate the main costs and benefits associated with winter cover crops. Costs included expenses associated with cover crop seeds, planting, termination, financial losses due to the harvest complications with cash crops, depreciation of machinery and the opportunity cost of time spent learning to grow winter cover crops. Benefits included increased income from greater yields; reductions in expenses associated with soil erosion control, nutrient cycling, weed control and mycorrhizal fungi colonization; reduced tillage operations and lower beehive prices for tomatoes and almonds, respectively; and ecosystem services such as increased soil organic matter, reduced surface water runoff and soil-carbon storage. The benefit of improved soil function and subsequent impacts to water management were not included in the model for baseline conditions but were addressed in model simulations.

Agricultural prices and management costs associated with winter cover crops serve as the primary data to estimate the economic viability of cover cropping. First, data on prices and costs were collected from the Cost and Return Studies compiled by the University of California Cooperative Extension [Turini et al., 2018, Duncan et al., 2016] as well as a collection of scientific publications on cover crop adoption across the U.S. [Auffhammer, 2018, Creamer et al., 1996, Gravuer, 2016, Malik et al., 2000, Nearing et al., 2017, Pratt et al., 2014, Rahmani et al., 2004, Robinson et al., 2014, Sarrantonio and Gallandt, 2003, Swan et al., ].

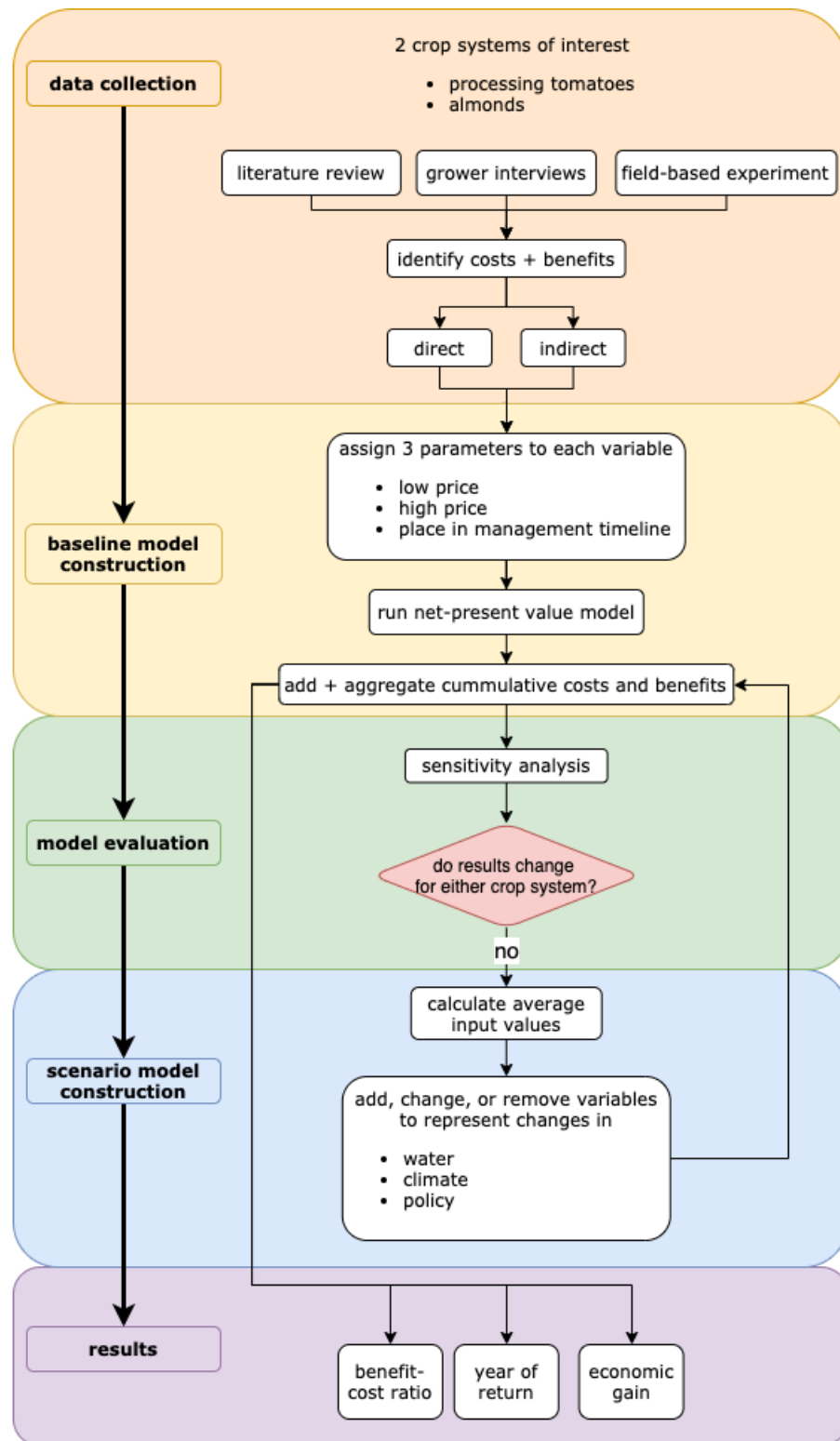


FIGURE 2.1. Flow chart of experimental design for chapter 2.



Second, semi-structured grower interviews were conducted (Table 2.1) to ground-truth results from the literature and establish a timeline for the costs and benefits associated with winter cover crop adoption. Researchers received IRB exemption 1007081-1 to conduct the interviews, which took place from 2017-2018. The sample included growers participating in a study supported by a California Department of Food and Agriculture Specialty Crop Block Grant (grant agreement #15037). The growers recommended additional growers to participate in the interview process, and the final sample of twelve growers reflected the diversity of operations throughout the region (i.e. a range of climates, crop types, management strategies and sizes of farming operations). The sample of growers included six winter cover crop adopters, two non-adopters and four growers who were undecided.

Growers received a list of questions and conversation topics before the interviews were conducted. The process changed iteratively and subsequent interviews were informed by the successes and challenges of previous ones [Watt, 2007]. The interview process slowly adapted from a strict survey to a fluid conversation, allowing time for trust to build between the interviewer and interviewees. Descriptive data such as physical characteristics of the farm, anecdotal experiences and real or perceived monetary costs and benefits were compiled in a database to describe thematic trends in the interviews. These trends provided data for analysis and informed subsequent design of our research methodology based on the grounded theory approach [Bitsch, 2005].

Third, data from the aforementioned field experiment was used to inform the development of model simulations [DeVincentis et al., ]. The field experiment included eleven agricultural fields of specialty crops that are either active farms or research sites. During the experiment, the University of California team collected a variety of soil and agronomic data to describe water movement in the soil of fields with winter cover crops versus those of fields without cover crops. These data and the time spent working in the agricultural community informed the adjustment of model parameters used to simulate possible changes to climate, water availability and policy that may affect agricultural production in the Central Valley.

**2.3.2. Model construction and evaluation.** We built a net present value model to estimate the cumulative economic value of winter cover cropping. All inputs in the model were costs or benefits related to winter cover crop adoption that would cause a change to baseline profits [Bergtold

TABLE 2.1. Details from cover crop informational interviews with growers throughout California’s Central Valley.

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**A sample of interview questions:**

How did you decide to start farming?  
 Can you tell us a brief history of your operation?  
 What type of crops do you grow? How many acres? For how many years?  
 What factors do you consider when deciding how many acres to grow?  
 Rank importance of these inputs in determining the success of your operation: Money, land, water, labor, pesticides, weather  
 Do you use any monitoring equipment?  
 What type of cover crops do you grow? How many acres? For how many years?  
 Why did you decide to use cover crops?  
 Can you quantify the costs and benefits of cover cropping and other conservation strategies for your operation?  
 What costs have you incurred from cover cropping? Seed, labor, risks?  
 What benefits have you incurred from cover cropping? Soil health, reduced inputs (fertilizer, pesticide, labor)?  
 Have you seen your water use change since you adopted cover crops or other conservation strategies?  
 Do you encourage other growers to cover crop? What are your reasons?

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**Notable interview excerpts:**

It’s a fine line of when am I going to save water [with cover crops]. Most times it is negligent.  
 I do think over time cover crops will make an operation more profitable. You’ll incur less costs and water. Better fertility, yield, and disease resistance.  
 From what it used to be, we now use at least 30% less water. I think it’s due to a combination of the organic matter increasing and field capacity increased so the water that we put in the soil stays longer.  
 There’s a trade-off between efficiency and flexibility - we are too big to be inefficient and you need to be flexible to cover crop.

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et al., 2017]. Our data set includes values for fifteen variables (Table 2.2) that we calculated based on underlying raw data from various sources, as detailed in the appendix. These fifteen inputs were labeled as either direct or indirect costs and benefits and assigned two monetary values to capture a range of possible prices, reported in 2018 US dollars per acre. The greatest challenge was to assign monetary value to perceived costs and benefits that vary greatly across operations, but we were able to do so by computing average values from grower interviews. Winter cover crops were assumed to be seeded on 100% of acreage for tomato fields and to cover 75% of acreage in almond orchards based on common planting practices.

The monetary values for each input were incorporated into the model at specific years when that cost or benefit was experienced. Years were chosen based on considerations from the grower interviews and expert opinions of agricultural professionals. These values were discounted to the present using a discount rate of 2.6% to incorporate the future value of money [USDA, 2019]. An advantage of this approach is that it provides both a visual representation of the long-term accumulation of costs and benefits and the present discounted value of the long-term use of a management practice, which may drive grower decision-making.

TABLE 2.2. Summary of monetized costs and benefits associated with winter cover cropping in two specialty crop systems in California’s Central Valley. Low and high monetary values are calculated by the authors based on raw data from various sources (detailed in the appendix) and are reported in 2018 US \$ per acre. These values were used to construct baseline scenarios of winter cover crop adoption.

Budget components	Low value (\$)	High value (\$)	Years of occurrence
<b>Processing tomatoes</b>			
Direct costs			
Seed	24	90	1 to 10
Planting (labor)	9.61	19.21	1 to 10
Termination (labor)	19.21	38.42	1 to 10
Indirect costs			
Harvest complications with cash crops	119.33	1872.45	every 5 years
Depreciation of machinery	3.75	22.5	1 to 10
Opportunity cost of time spent learning to grow cover crops	192.1	384.2	first 5 years
Direct benefits			
Increased yield	119.33	312.08	5 to 10
Soil erosion control	7.63	15.26	5 to 10
Nutrient cycling	19.8	118.8	5 to 10
Weed control	1	6	5 to 10
Mycorrhizal fungi colonization	29.16	583.29	5 and 10

TABLE 2.2. Summary of monetized costs and benefits associated with winter cover cropping in two specialty crop systems in California’s Central Valley. Low and high monetary values are calculated by the authors based on raw data from various sources (detailed in the appendix) and are reported in 2018 US \$ per acre. These values were used to construct baseline scenarios of winter cover crop adoption.

Budget components	Low value (\$)	High value (\$)	Years of occurrence
Reduced tillage operations	15	25	5 to 10
Indirect benefits			
Increased soil organic matter	21.72	46.54	5 to 10
Reduced surface water runoff	0.87	4.76	1 to 10
Soil-carbon storage	4.36	22.53	1 to 10
<b>Almonds</b>			
Direct costs			
Seed	15	64.5	1 to 4
Planting (labor)	7.69	15.38	1 to 4
Termination (labor)	15.38	30.76	1 to 3
	22.5	75	4 to 30
Indirect costs			
Harvest complications with cash crops	47.56	970.15	every 5 years
	65.39	1333.96	
Depreciation of machinery	1.8	10.79	1 to 30
Opportunity cost of time spent learning to grow cover crops	205.06	410.13	1 to 5
Direct benefits			
Increased yield	11.89	40.42	3
	23.78	80.85	4
	47.56	161.69	5
	65.39	222.33	6 to 30
Soil erosion control	5.72	11.44	5 to 30

TABLE 2.2. Summary of monetized costs and benefits associated with winter cover cropping in two specialty crop systems in California’s Central Valley. Low and high monetary values are calculated by the authors based on raw data from various sources (detailed in the appendix) and are reported in 2018 US \$ per acre. These values were used to construct baseline scenarios of winter cover crop adoption.

Budget components	Low value (\$)	High value (\$)	Years of occurrence
Nutrient cycling	11.41	68.46	5
	14.51	87.04	6 to 30
Weed control	3.03	18.17	5 to 30
Mycorrhizal fungi colonization	21.87	437.47	every 5 years
Discounted beehives	4.71	28.25	3
	9.42	56.5	4
	18.83	112.99	5
	23.54	141.24	6 to 30
Indirect benefits			
Increased soil organic matter	16.29	34.9	5 to 30
Reduced surface water runoff	0.65	3.57	1 to 30
Soil-carbon storage	3.27	16.9	1 to 3
	1.64	8.45	4 to 30

Separate models were built for each system to address crop-specific management strategies. The time horizons for tomato and almond operations were 10 and 30 years, respectively, to reflect typical crop rotation patterns. Winter cover crop type remained constant every year in the tomato model, while an alternative structure was developed to mimic a more realistic adoption of winter cover cropping in almond orchards. It was assumed that the first three years of an almond orchard were used to add biomass to the soil without complicating harvest. For these years we modeled the use of a green manure where a winter cover crop seed was planted and terminated similarly to the row crop fields, with residue being incorporated into the soil. In subsequent years (4-30),

we assumed almond growers would experience reduced benefits from planting an annual reseeding variety once to mimic native vegetation and minimize management.

To demonstrate how each budget component was valued on a per acre basis, we detail how the cost of winter cover crop seeds was quantified. The direct cost of seeds was determined to be in the range of \$24-90 in years 1-10 for tomatoes and \$15-65 for years 1-4 for almonds. These values are based on conversations with farmers, extension specialists and advisors, and seed company representatives. The range in price describes the variety of potential seed mixes that are commonly used for winter cover cropping in California’s Central Valley for annual and perennial systems. The mixture considered for tomato operations was assumed to be a small grain forage mix (e.g. bell beans, winter peas, common vetch) purchased for \$0.40-0.75 per lb. and planted at a rate of 60-120 lbs. per acre. The mixture considered for almonds was assumed to be a more expensive clover mix purchased for \$1-2.15 per lb. planted at a lower rate of 20-40 lbs. per acre. Detailed explanations of the calculations for the remaining inputs can be found in the appendix.

**2.3.3. Baseline impact of winter cover crops.** To test our first hypothesis that the benefits of winter cover cropping accrue over time, we used the net present value models to calculate how the baseline economic performance of tomato and almond operations would change with the addition of winter cover cropping. We used these numbers to calculate benefit-cost ratios (BCR) with Equation 4:

$$Equation4 : BCR = \frac{\sum_{t=0}^{t=T} \frac{Benefits_t}{(1+r)^t}}{\sum_{t=0}^{t=T} \frac{Costs_t}{(1+r)^t}}$$

where  $t$  denotes the time period when the value is incurred,  $T \in (10, 30)$  is the time horizon considered, and  $r$  is the discount rate. A benefit-cost ratio greater than 1 is equivalent to a positive net present value, i.e. total discounted benefits exceed total discounted costs over the time period considered. We report benefit-cost ratios and temporal points of financial return to determine the economic profitability of incorporating winter cover crops into both specialty crop operations.

**2.3.4. Model sensitivity.** A sensitivity analysis was performed to test the robustness of the baseline modeling results and identify which inputs were most influential on the model results. An average value for each input was used in the models and the influence of each input was tested by

replacing the average value with its low and high ranges, culminating in 30 model runs to test the significance of the 15 variables in each cropping system model. This method of sensitivity analysis accounted for both the range of input prices between low and high values and the proportion of each input to the overall budget.

**2.3.5. Counterfactual scenario construction.** To explore the second hypothesis that the economic profitability of winter cover crops may switch in response to changes in California's agricultural production context, we simulated six scenarios that describe social and biophysical changes to agricultural operations (Table 2.4.2). Scenarios were chosen based on analysis from the farmer interviews and results from the sensitivity analysis that revealed which variables had the most leverage. For each of the six scenarios, the baseline model was constructed using average input values and one or more variables were either changed, removed or added to simulate the circumstances.

Climate change will alter agricultural production in California and the potential economic consequences of these impacts warrant consideration [Pathak et al., 2018]. Scenario 1 addresses this by calculating how climate change will impact the baseline profit of an average operation growing winter cover crops. This scenario models the potential impact of four simultaneous climate changes, which include warmer temperatures and more frequent extreme weather events (e.g. heat waves, floods, and droughts). We assumed that the prices of irrigation water would increase due to warmer temperatures that alter the timing of spring runoff, which is a critical component in the network of surface water storage facilities that move California's water from the northern part of the state to the southern part [Hanak et al., 2011]. The price of water was added to the model, estimated at a 10-25% increase to the average per acre irrigation costs, which are \$635.32 for tomatoes and range from \$229.13 in the first year to \$874.86 past the fourth year for almonds [Turini et al., 2018, Duncan et al., 2016]. This scenario also addresses changes in yield due to more heat waves, which are predicted under climate change [Pathak et al., 2018]. Tomatoes and almonds were treated differently because more heat waves may result in greater yields for tomatoes, but lower yields for almonds. Yield benefits increase or decrease 5% for tomatoes and almonds, respectively. Lastly, Scenario 1 includes the impact of more frequent floods and droughts. This scenario incorporates a 10% increase in benefits from soil erosion control due to cover crops

in response to more frequent floods, and a 3-inch increase in irrigation requirements in response to more frequent droughts and subsequent depletion of soil moisture.

Three water scenarios explore how water-related parameters impact the profitability of winter cover cropping. These are important to consider under the lens of compliance with new resource management policies in California and a changing hydrologic landscape. Sustainable agriculture will require field conditions to improve so applied water (e.g. precipitation and irrigation) is used more efficiently as water becomes more scarce, expensive and polluted [**Jury and Vaux, 2005**]. Scenario 2 addresses this by simulating better field conditions when cover crops improve infiltration, retention and re-distribution of soil water. These conditions could improve water management conditions on agricultural fields and potentially reduce irrigation costs. This scenario simulated an ideal situation where winter cover crops increase soil water availability for summer cash crops and reduce irrigation requirements by 30%. Water costs per acre are \$635.32 for tomatoes and range from \$229.13 in the first year to \$874.86 after the fourth year for almonds [**Turini et al., 2018, Duncan et al., 2016**]. Scenarios 3 and 4 compare the profitability of winter cover cropping in the northern and southern regions of the Central Valley, which face different hydrologic constraints, including annual precipitation and the cost of surface water deliveries. These simulations increase and decrease the frequency of harvest complications with cash crops, which increases to every 3 years and decreases to none in the northern and southern parts of the Central Valley, respectively.

Two policy scenarios explore the impacts of growing winter cover crops under a new regulatory landscape in California. Scenario 5 simulates the economic profitability of growing winter cover crops while receiving subsidies for their ecosystem services. A range of values was used to identify the price necessary to break even, starting at \$55 per acre based on average prices of government subsidies for cover cropping throughout the U.S. Scenario 6 simulates an increase in the value of carbon that cover crops store in the soil through agricultural mitigation. The soil-carbon sequestration variable was altered by doubling the price of carbon [**Frances et al., 2017, Nordhaus, 2017**]. These numbers reflect an increased societal valuation of carbon sequestration that could be feasible if law makers and society focus on the implementation of climate change mitigation policies.



## 2.4. Results and discussion

The following results are based on the output of the models that calculate the net present value of costs and benefits from growing winter cover crops in California. We estimate the profitability of this practice by calculating baseline benefit-cost ratios for winter cover cropping in operations that produce tomatoes and almonds over 10- and 30- year horizons, respectively. After testing the baseline models with a sensitivity analysis, we conduct a scenario analysis that shows how the incentives for adoption vary as climate, water availability and environmental regulations change. Winter cover cropping in California may be profitable in the long-term, but this depends on the crop system, extent of irrigation savings due to improved soil function, access to financial subsidies and climate change impacts.

**2.4.1. Baseline impact of winter cover crops.** Winter cover cropping is an investment in the long-term viability of agricultural operations. The value of this conservation practice is evident when using a planning horizon beyond the next planting season. The annual breakdown of the cumulative modeling results reveals that benefits and costs accrue differently over time, supporting our first hypothesis that the value of winter cover crops is not captured in an annual analysis (Figure 2.2). The costs vary significantly from year-to-year depending on the occurrence of harvest complications with cash crops. Additionally, only a small portion of cumulative benefits are indirect, which suggests that the existence of social benefits (i.e. benefits accruing to those external to the decision-maker) are not a driver of low adoption rates. Modeling results also reveal different experiences for tomato and almond growers, which experience cumulative benefit-cost ratios of 0.6 and 1.2, respectively.

Results from the sensitivity analysis validate the performance of the models and identify which inputs had the most leverage. The two crop models change distinctly due to changes in variable parameter values (Figure 2.3). The almond model is more sensitive and displays a wider range of possible benefit-cost ratios. The variables that affected the benefit-cost ratios most were harvest complications with cash crops (i.e. reduced revenue), yield increases (i.e. increased revenue) and mycorrhizal fungi colonization (i.e. foregone cost of soil amendments).

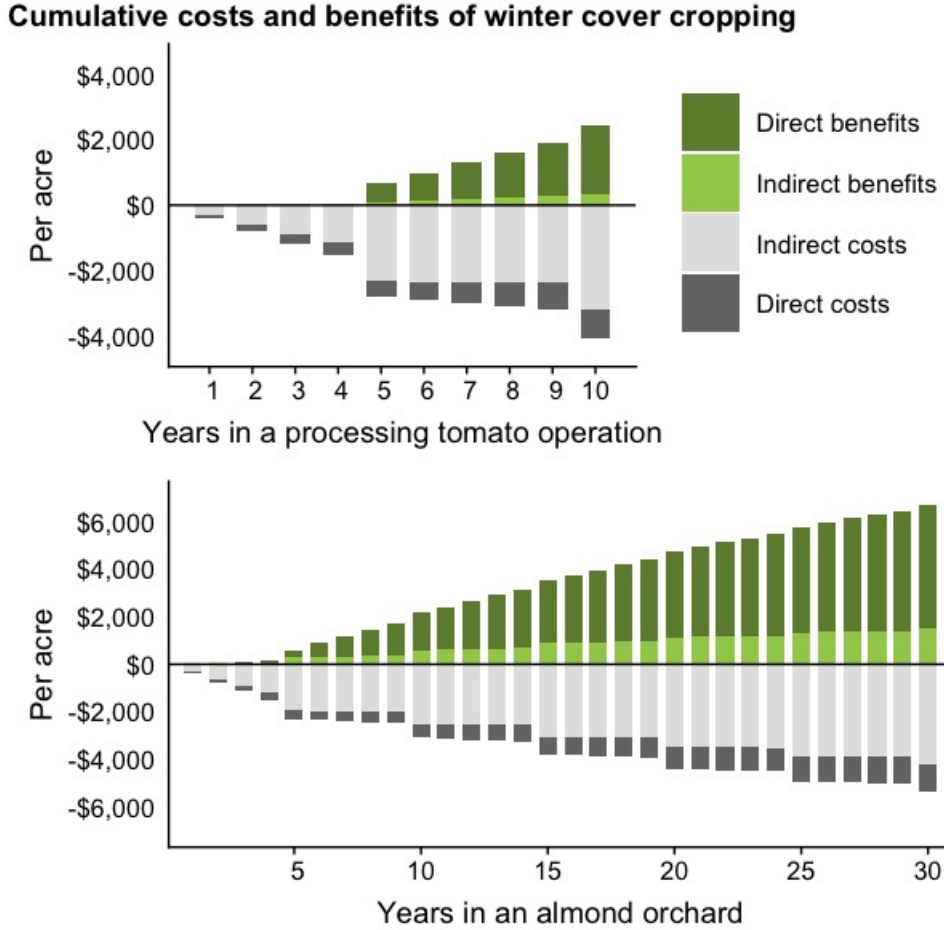


FIGURE 2.2. Breakdown of cumulative costs and benefits due to winter cover cropping in processing tomato and almond operations. Values are reported in 2018 US dollars per acre and discounted annually. Benefits and costs are separated based on their designation as 'indirect' or 'direct' costs or benefits. These values reflect model results under baseline conditions.

Through 30 baseline model runs, the benefit-cost ratio is never above 1 for tomatoes but is closest to breaking even when the cost of harvest complications with cash crops is minimized. This variable is estimated to be less significant in almond production, which contributes to the almond system having a benefit-cost ratio more consistently over 1. The harvest complication variable represents the potential for winter cover crops to complicate the harvest of summer cash crops, a risk that was revealed from grower interviews. These complications look slightly different for the two cropping systems of interest. For tomato growers, late winter rain could delay termination of a

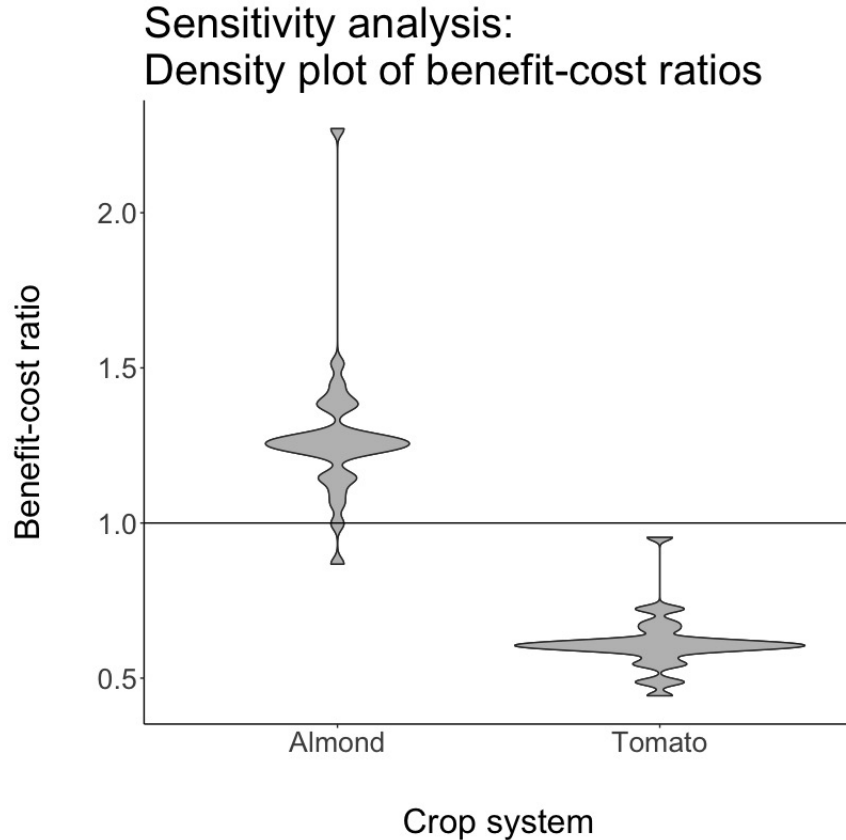


FIGURE 2.3. Density distribution plot of results from sensitivity analysis of net present value models for growing winter cover crops in California. The analysis explored the impact of the range of prices for inputs to models for almond and tomato production systems.

winter cover crop due to wet field conditions. This could in turn delay their tomato transplanting schedule, which is designed to provide weekly harvests to meet contracts with tomato canneries throughout the summer. For almond growers, winter cover cropping could complicate summer harvests that require sweeping up almond hulls off the orchard floor. The industry standard is to have a ‘clean floor’ by August, however a cover crop could persist between rows and potentially interfere with harvest equipment. These harvest complications were valued as infrequent revenue losses (see appendix).

These results led to further modeling to explore the impact of harvest complications. When this variable is excluded from the analysis, both crop systems experience an average benefit-cost ratio of 1 or greater and growing winter cover crops is profitable. However, if this variable is included in the

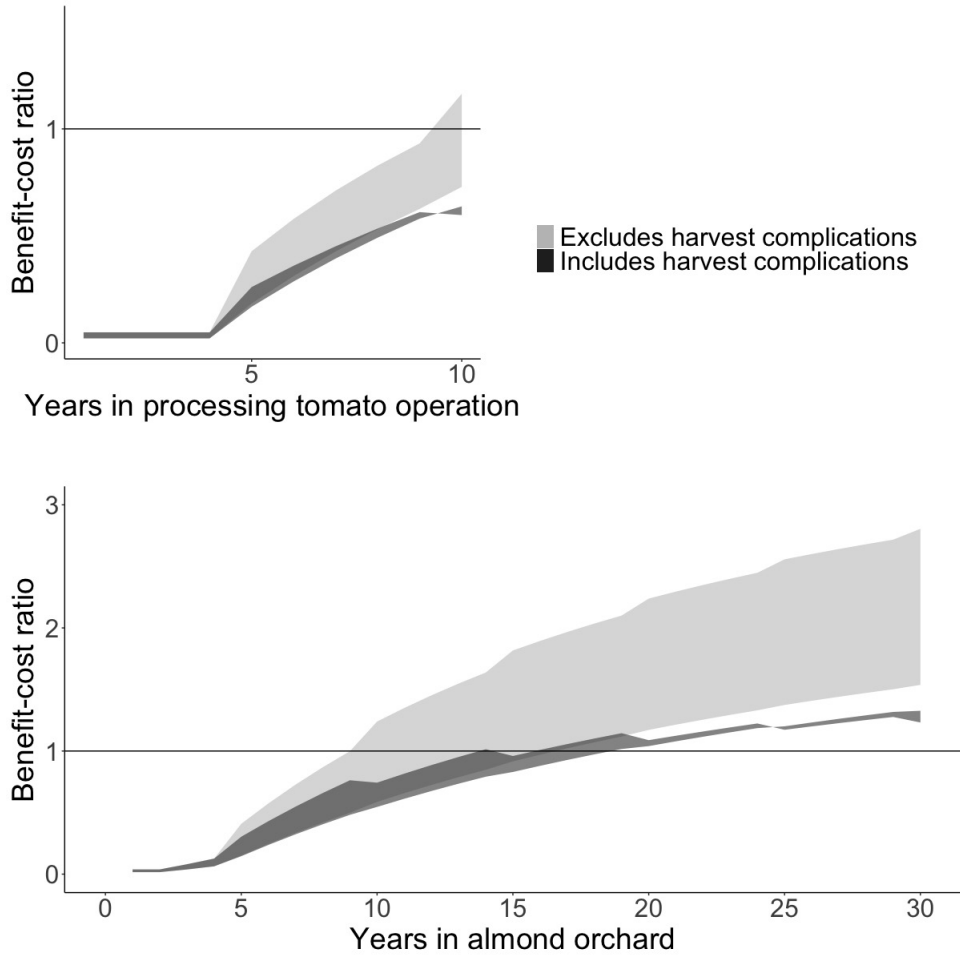


FIGURE 2.4. Range of possible benefit-cost ratios experienced by specialty crop operations practicing winter cover cropping in California’s Central Valley under baseline conditions.

analysis, the average benefit-cost ratios fall to 0.6 for tomatoes and 1.2 for almonds, indicating that total benefits eventually outweigh total costs for operations growing almonds, but not tomatoes (Figure 2.4).

Growing winter cover crops in California’s Central Valley can increase baseline profit for some operations. In average baseline conditions that include harvest complications every fifth year, perennial crop systems growing almonds can experience economic benefits between 14-19 years after the start and continuation of this conservation practice. Annual crop systems growing winter cover crops between crop rotations that include tomatoes do not see an economic return on average in the 10-year cycle that was modeled, unless harvest complications are removed from analysis.

These results may not represent all tomato and almond operations because the baseline ratios are derived from average costs and benefits; farm-specific ratios would vary with site-specific factors. For example, if an operation experiences the upper-bound values for benefits and lower-bound values for costs, then benefits outweigh costs for both production systems after 9 years. The range of possible experiences that this model predicts for tomato operations (Figure 2.4) is consistent with the reality that some annual crop farmers adopt winter cover crops, while the practice may not be profitable on average for everyone.

**2.4.2. Counterfactual scenarios.** The validated baseline models were adjusted to shed light on the future viability of winter cover cropping by simulating hypothetical changes in California's agricultural production and regulatory context. The resulting benefit-cost ratios challenge our second hypothesis that changes in climate, water access and policy can switch the economic viability of winter cover cropping (Table 2.4.2). For a majority of the scenarios, the benefit-cost ratios do not switch, and the value remains less than 1 for tomatoes and greater than 1 for almonds (Figure 2.5). Almond orchards with winter cover crops appear to be resilient in this sense to regulatory disturbances, while processing tomato operations may require specific circumstances to experience profitability.

Climate change will challenge the economic viability of winter cover cropping in California. The climate change scenario 1 models the simultaneous occurrence of four climate changes and their related impacts to agricultural production. The cumulative benefit-cost ratios are below 1 for both crop systems, indicating that the combination of increased temperatures and frequency of extreme weather events cause the costs of cover cropping to increase more than the benefits in the face of climate change.

Winter cover cropping is profitable on average for tomato operations in two scenarios. First, growers will experience a net economic gain if winter cover crops cause a 30% reduction in summer irrigation requirements due to improved soil function. While this is an ideal scenario, it is important to consider because some farmers in the Central Valley report having had this experience. Second, a tomato grower can profitably grow winter cover crops if they experience no risk of harvest complications, as shown in scenario 4. However, they may suffer economic losses if late winter rains interfere with winter cover crop termination. Growers that experience harvest complications with

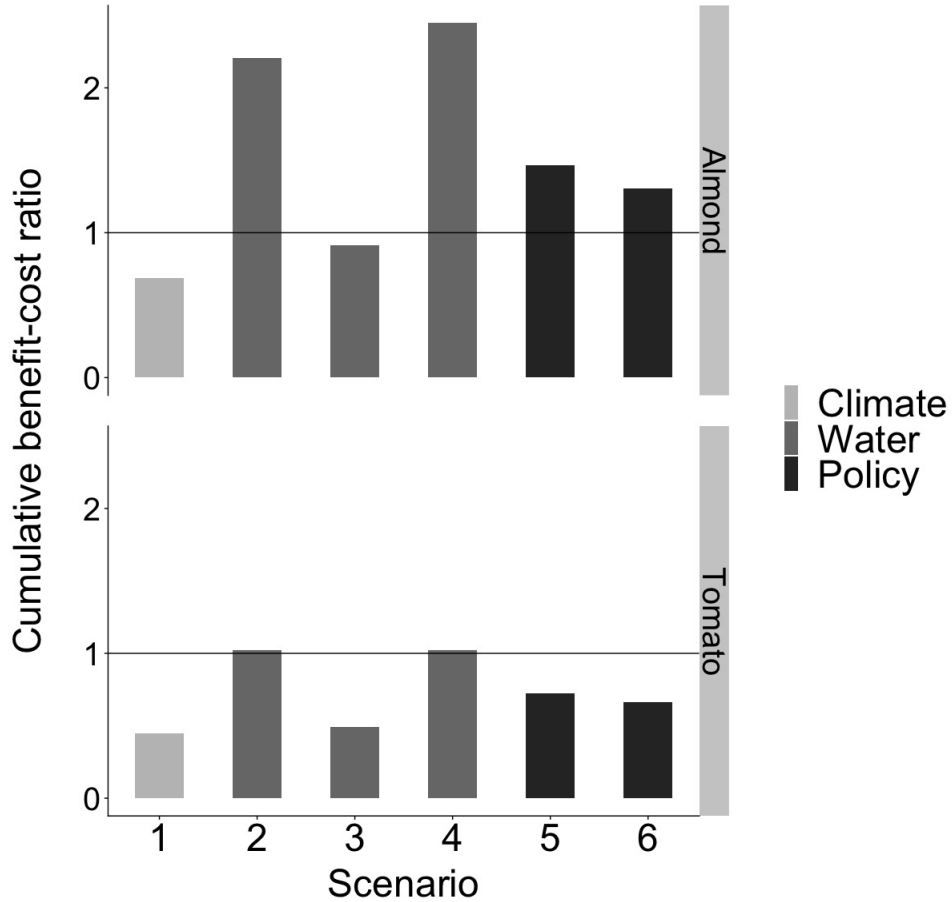


FIGURE 2.5. Benefit-cost ratios of growing winter cover crops under various scenarios that simulate changes to California’s agricultural landscape. This figure should be viewed in conjunction with Table 2.4.2 that references each scenario.

tomatoes which prevent them from meeting the deadlines of inflexible contracts with canneries will not experience the same economic benefits of this land management practice, as shown in scenario 3.

There is opportunity for policy interventions and government subsidies to incentivize winter cover crop adoption, but the details of implementation require careful consideration of a grower’s regulatory landscape. To encourage adoption, policies should offer incentives that are crop-specific because tomato and almond farmers do not experience the same degree of economic return from cover cropping with subsidies, as shown in scenario 5. The price point of subsidies to incentivize winter cover cropping must increase. Prices used to model subsidies in scenarios 5 and 6 were based on current rates offered by the USDA and historical price of carbon on the California market. The

simulation of these subsidies did not help tomato farmers meet a breakeven point. Further variable manipulation showed that there are three subsidies that make winter cover cropping a profitable soil management strategy for tomato operations: a subsidy of at least \$175 per acre annually or \$550 per acre for the first three years of the practice or a subsidy that reflects a social price of carbon around \$600 per ton, assuming that winter cover crops can sequester 0.3 tons of carbon per acre.

TABLE 2.3. Description of benefit-cost ratios (BCR) for scenarios that simulate future changes in climate, water and policy in California. Values are reported at the end of the systems' life cycles – 10 and 30 years for tomato and almond, respectively.

Variable type	Scenario description	Benefit-cost ratio		Percent change to baseline benefit-cost ratio	
		Tomato	Almond	Tomato	Almond
<b>Scenario 1 explore potential impacts of climate change by combining the following variables</b>					
1 Cost	Warmer temperatures change spring runoff timing, thereby decreasing the reliability of surface water deliveries and increasing water prices	0.45	0.68	-26	-45
	More frequent heat waves affect agronomic performance of tomatoes and almonds, increasing or decreasing yields respectively				
Benefit & cost	Cover crops reduce erosion losses during more frequent floods				
Cost	More frequent droughts increase irrigation requirements of cash crops				
<b>Scenarios 2 - 4 explore potential hydrologic changes</b>					

		Winter cover crops increase soil-water					
2	Benefit	in the winter, thereby decreasing summer irrigation requirements by 30%	1.02	2.21	69	77	
		There is a greater risk of harvest complications with cash crops, which					
3	Cost	is likely to be experienced in the Northern part of the Central Valley due to the unpredictability of spring precipitation	0.49	0.91	-19	-27	
		There is no risk of harvest complications with cash crops, which is likely to be					
4	Benefit	experienced in the Southern part of the Central Valley due to the predictability of spring precipitation	1.02	2.45	69	96	
<b>Scenarios 5 - 6 explore potential policy changes</b>							
		State policies incentivize cover					
5	Benefit	cropping through a subsidy for the ecosystem and societal services that winter cover crops provide	0.73	1.46	20	17	
		State subsidizes carbon storage					
6	Cost	through agricultural practices such as winter cover crops	0.66	1.31	10	5	

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**2.4.3. Impacts for producers and policymakers.** The results of this research are critical for both producers and policy makers as they strive to meet the challenges of agricultural production under California’s changing environment. For producers, winter cover crops can be economically viable under certain circumstances, but they should be considered a long-term investment. Almond operations appear to be resilient systems that could likely withstand the financial requirements of



winter cover cropping, while tomato growers should more heavily weigh site-specific factors of their operations before investing in this practice. For policy makers, our findings show that access to sufficient government subsidies could increase winter cover crop adoption in both annual and perennial crop systems.

To obtain positive net benefits from winter cover cropping, growers must consider a long planning horizon and value ecosystem services. We speculate that farmers should consider several on-farm implications of winter cover crops to ensure their profitability. First, the largest threat to winter cover crop profitability in processing tomatoes appears to be the potential for harvest complications with cash crops and subsequent contractual non-compliance. Potential solutions are to use warm weather cover crops that do not have the same management complications in response to late winter rains or to plant winter cover crops on a portion of the cropland, specifically that which will be harvested later in the summer. Winter cover cropping in tomatoes becomes a profitable practice without this threat, indicating that they could be a profitable investment if they are grown with the care and attention of a cash crop. This finding is relevant because the benefits of winter cover cropping clearly outweigh the costs for crop systems that are not beholden to pre-determined dates of sale. There is ample opportunity for growers throughout California and the rest of the country to take advantage of the positive net present value of winter cover cropping as long as they have flexible contractual requirements and can wait for the long-term return on investment.

California growers work within a complicated network of hydrologic constraints that may impact the profitability of winter cover cropping. If growers can reduce their summer irrigation requirements through the use of winter cover crops, the practice could pay for itself. In the northern part of the Central Valley, late winter rains that complicate termination of winter cover crops are more likely, but water is generally less expensive in this region. In the southern part of the Central Valley, late rains are less likely, while water can be significantly more expensive. Farmers in all parts of the Central Valley may have various water-related winter cover crop concerns.

Policy interventions affect certain crop systems more than others, complicating the development of an incentive structure. Governmental programs that offer payments for ecosystem services could enhance the profitability of winter cover cropping in California, but, in light of our results, the payments likely need to be larger and more accessible than they have been in the past. According

to our analysis, for an average tomato operation to profitably grow winter cover crops (holding all other variables constant), growers would need to receive a payment of nearly \$550 for the first 3 years or \$175 annually for 10 years. These values are significantly higher than the current rates provided through cost-share by the USDA for on-farm conservation practices, however they are on the scale of incentives currently available in California through the Healthy Soils Program by the California Department of Food and Agriculture. Only 6,000 acres of farmland in California annually received a subsidy for cover cropping from the USDA between 2015-2018 (personal communication with Hudson Minshew). High-value crops grown in California, such as tomatoes and almonds, are more expensive to produce than staple crops grown in the Midwest, where cover crop adoption is more common. Growers may adopt cover crops only if their subsidy covers a significant portion of their average annual operating costs.

Subsidies for the climate change mitigation effect of cover cropping could also enhance their profitability but require a ten-fold increase in the price of carbon. This may be feasible if law makers and society focus on the implementation of climate change mitigation policies and dedicate sufficient funds to incentivize sustainable agricultural practices.

These subsidies monetize ecosystem services provided by winter cover cropping, which include the indirect benefits of increased soil organic matter, reduced surface water runoff and soil-carbon storage. These indirect benefits are both felt by individual growers and have spillover effects to society at large. These benefits may be experienced by the next grower farming the land, who does not need to build up their soil carbon, a grower's downstream neighbor who has access to cleaner water or future generations that can rely on a consistent food supply amidst climate uncertainties.

**2.4.4. Limitations and future work.** Our work to understand cover crop adoption incentives can be expanded in future research. First, the model could be improved by including the monetary values of components of the budget that are difficult to quantify, such as changes in insect biodiversity, biogeochemistry and greenhouse gas emissions. For example, our model could more clearly address the complicated trade-off of using carbon: greenhouse gases are emitted when diesel-powered equipment is used to plant and terminate winter cover crops, but cover crops naturally sequester carbon in the soil. One could also explore the implications of alternative termination methods, such as grazing and forage. Additionally, the rich heterogeneity across growers is not

captured in our analysis of average benefits and costs. The monetization process required simplifications and assumptions that may not reflect site-specific conditions for all specialty crop growers in California. Lastly, our results are location and crop specific to tomato and almond operations in the Central Valley of California and there is no prescription for all California farms. However, this model could easily be modified to different systems and locations with appropriate data.

Despite these limitations, this research provides significant contributions to the study of conservation agriculture practices by shedding light on the possible reasons for low adoption of winter cover cropping in California’s specialty crop systems. It is the first modeling effort to evaluate the economic impact of cover cropping in these high-value crop systems in California and the results are relevant to many types of agricultural systems. This model improves on previous methodologies by validating parameter estimates and literature values through grower interviews and field datasets, ensuring that our research is grounded in reality. We use this novel method to analyze both the current situation and look to the future through counterfactuals that explore several possible futures of agricultural production.

## 2.5. Conclusions

This research highlights the importance of valuing soil management practices, such as winter cover cropping, to gauge their role in the changing agricultural landscape of California. A net present value model describes the economic value of winter cover cropping to shed light on barriers to adoption. The model confirms the hypothesis that winter cover crops have a long-term payoff because benefits accrue slowly over time. Winter cover crops are likely to be viable in almond and tomato operations that do not experience harvest complications. While climate change impacts may threaten the viability of winter cover cropping, benefits outweigh costs to a larger extent if growers receive sufficient subsidies to capture the societal benefit of ecosystem services and if they can reduce their summer irrigation requirements. Growing winter cover crops may have significant long-term benefits for individual farms and society as a whole in California and beyond.

## CHAPTER 3

# Farmer participation in common-pool resource governance reforms: the case of groundwater management in California

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### 3.1. Abstract

Farmers are often critically important to the success of common-pool resource governance reforms. Nevertheless, their participation in these off-farm reform processes has received limited research attention. This paper investigates farmer participation in state-mandated common-pool resource governance. Using groundwater governance in California as a case study, we show that existing social networks, in combination with asymmetries in resource access within the farming community, and a collective identity framed against central government intervention, explain participation and representation in groundwater governance processes. An important governance paradox has emerged, in which groundwater-dependent users are unequally represented in the very groundwater management agencies that have been developed to protect them. This case sheds light on documented shortcomings of common-pool resource governance reforms and aims to inform the design of future reform processes.

### 3.2. Introduction

As the need for sustainable natural resource management continues to grow worldwide, agriculture often plays a pivotal role in environmental governance reforms [**for Economic Co-operation and Development, 2008**]. Agricultural stakeholders, such as farmers, are often required to participate in the design and implementation of such reforms [**de Loë et al., 2015, Hardy and Koontz, 2010, Primdahl et al., 2013**]. Adoption of on-farm conservation measures designed

to reduce environmental impacts from agricultural practices are a common and well-researched reform example [**Baumgart-Getz et al., 2012, Knowler and Bradshaw, 2007, Prokopy et al., 2008, Prokopy et al., 2019**]. The participation of farmers in off-farm environmental governance processes has received less attention, and importantly, it is likely that the behavioral motivations to participate in these reform processes are quite different.

Of particular concern in this paper is the participation of farmers in top-down, state mandated reforms to create local common-pool resource (CPR) structures (i.e. management entities and institutions). The development of CPR governance structures has become a dominant environmental governance approach worldwide [**Lemos and Agrawal, 2006, Schlager, 2007**]. Despite the important role farmers play in the success of CPR governance structures in agricultural landscapes, with few exceptions [**de Loë et al., 2015, Ferreyra et al., 2008, Hardy and Koontz, 2010, Primdahl et al., 2013**], their perspectives have often been overlooked [**Koontz, 2003**].

Farmers are being challenged to comply with and participate in CPR governance, on top of the day-to-day demands of their farm businesses, and an increasingly unpredictable climate. They are also dominant users of CPRs, such as water, which is a defining input for all crop and livestock operations. Their participation or non-participation in local water governance processes is key to understanding the feasibility and implications of proposed solutions that aim at reducing undesirable environmental impacts, increasing resilience to climate change, and improving water management [**Castilla-Rho et al., 2017**]. Understanding farmer perspectives and behavior is thus important for the success of environmental governance processes.

This paper investigates what motivates California farmers to participate in a state-mandated groundwater governance reform, the Sustainable Groundwater Management Act (SGMA). Using secondary and qualitative interview data from 27 farmers across the state, we find that existing social networks [**Bolding, 2004, Wester, 2008**] in combination with asymmetries in resource access within the farming community [**Agrawal and Gibson, 1999, Ribot and Peluso, 2003**], and a collective identity [**Abers, 2007**] framed against governmental intervention [**de Loë et al., 2015, Ferreyra et al., 2008, Hardy and Koontz, 2010, Niles et al., 2013, Stock et al., 2014, Taylor and Van Grieken, 2015**] explain participation and representation in groundwater governance processes. Interestingly, experience with short and long-term environmental changes

is not a consistent driver of farmer participation in groundwater governance reform processes. This case study shares farmers' first-hand experiences with the California groundwater reform and reflects on the failed promise to create equitable CPR governance structures.

In the next section we discuss theoretical tools for analysis followed by a description of the policy context in California. Our methods approach is then presented, followed by a discussion of results. In conclusions, we address the potential implications of asymmetrical participation in environmental governance processes.

**3.2.1. Untangling participation in environmental governance processes.** The main focus of this paper is to understand farmer participation in environmental governance processes. We use foundations from environmental behavior, political ecology and common-pool resource governance theory to inform our understanding of farmer participation in SGMA processes.

Research in environmental behavior has hypothesized that catastrophic climate events have the greatest likelihood of altering beliefs, risk perceptions, behavior and policy preferences toward climate change [Gifford, 2011, Sanderson and Curtis, 2016, Weber and Stern, 2011]. Relevant to our work are a number of empirical studies that have looked at the impact of drought on modifying farmers' behavior [Carlton et al., 2016, Findlater et al., 2018, Lane et al., 2018, Niles et al., 2013, Schattman et al., 2016, van Duinen et al., 2015]. However, results have varied dramatically. Interestingly, Carlton et al. (2016) found that while farmers in the Midwest had a heightened risk perception toward the 2012 drought, this event had little impact on their attitudes toward climate adaptation actions. In California, Niles, Lubell and Haden (2013) found that farmers' greatest concern around climate change was an increase in government regulation, rather than water security and drought. This indicates that perceived resource scarcity [Casciari and Piskorski, 2005, Hillman et al., 2009] related to climate change, may be one among many potential drivers of farmer participation in environmental governance.

We use the overarching framework presented by Hoogesteger and Wester (2015) to study groundwater governance. They based their framework on the theory of access presented by Ribot and Peluso (2003), which focused on access rather than rights. Access is defined as "the ability to benefit from things – including material objects, persons, institutions, and symbols" [Ribot and Peluso, 2003]. Particularly for groundwater, a focus on access seems imperative since ability to

use this resource is more convoluted than merely defining groundwater rights. Groundwater access is primarily a question of private hydraulic property (i.e. wells), access to electricity or diesel to facilitate extraction (i.e. power pumps), and land ownership [Hoogesteger and Wester, 2015]. Hoogesteger and Wester (2015) emphasized three core concepts in their framework that are relevant to the case study: hydrosocial networks, political economy and discourses that define groundwater access.

Hydrosocial networks [Bolding, 2004, Wester, 2008] are configurations of resource-users, water resources, technology, and other material and productive resources that make water extraction, use and distribution possible [Mollinga, 2003]. These networks are thus constituted both by social actors and the natural, physical and technological environment that organize the groundwater socio-ecological system (SES) [Ostrom, 2010].

The political economy of groundwater enables access to land ownership, technology and other inputs, as well as the institutions which define productive relationships that organize rural communities [Clement, 2010]. Transnational markets of commodity chains, and agrarian and water policies are notable. Together they define who, where, for what purpose and at what cost, groundwater is extracted and used [Kumar et al., 2013, Levidow, 2013, Scott, 2011].

Discourses define groundwater access by influencing what is considered fair and acceptable resource use, legitimizing groundwater access [Clement, 2010]. Political and ideological convictions, as well as cultural norms, inform decision-makers at various scales, which in turn design policies and rules for groundwater governance [Ostrom, 1990, Molle, 2008].

Given the heterogeneity of farmers, who in practice are a community with distinct farm characteristics and access to technology, land, water and other resources, and social and political views [Rudnick et al., 2016, Agrawal and Gibson, 1999], their experience with CPR governance may be diverse. As such, farmers' motivations to participate may be driven by their various roles and capacities as producers, landowners or community members [Primdahl et al., 2013, Ribot and Peluso, 2003]. Thus, farmers may be 'commitment-driven', when maintaining and increasing social status in their communities is important, or 'capacity-driven', when they can overcome the transaction costs [Libecap, 1994, Ostrom et al., 1994, Williamson, 1987] associated with participating in collective management [Primdahl et al., 2013].

Leveraging existing social networks to develop new CPR governance agencies can enable coordination and trust [**Vangen and Huxham, 2005**], but farmers may belong to various (hydro)social networks that may not overlap. Their commitment may thus be related to various communities. This is important because those who are able to participate decide themselves with whom they want to collaborate and what they want to accomplish [**Henry et al., 2011**], challenging inclusion and adequate representation in governance processes [**Leach, 2006, Holley, 2010, O’Toole Jr and Meier, 2004**]. This may result in the formation of unbalanced decision-making bodies that do not consider the perspective of underrepresented groups, which can impact the representation of stakeholders from different sectors (e.g. environmental, municipal, rural residential) [**Bryson et al., 2006**], as well as representation within the farming community itself [**Kemerink et al., 2013**].

Participation in CPR governance has associated transaction costs that come out of defining, negotiating and coordinating collective management among various groups of resource-users [**Libecap, 1994, Ostrom et al., 1994, Williamson, 1987**]. The capacity to overcome these costs, such as time to go to meetings, access to meeting venues and information, staff and other resources, defines access to participation [**Holley, 2010, Ribot and Peluso, 2003**]. Thus, only those who can bear these costs [**Raab et al., 2015, Lubell et al., 2017**] may be able to engage in CPR governance.

Finally, political and ideological convictions, as well as cultural norms may also shape participation in environmental governance [**Ostrom, 1990**]. In regards to farmers, discourses on utilitarianism and libertarianism have been used to frame their collective identity [**Hoogesteger and Wester, 2015**]. For example, multiple studies have revealed that aversion to losing resource control through top-down regulations or legal mandates can drive farmer participation in local resource management [**Ferreira et al., 2008, Hardy and Koontz, 2010, Stock et al., 2014**]. In the face of inevitable government intervention, farmers may paradoxically seek to participate in CPR governance as a means to reassert their control over natural resources when they cannot get what they want without cooperating [**Méndez-Barrientos et al., 2018**].

**3.2.2. California as a case study.** California farmers face different climate-related challenges depending on their location in the state. However, most were affected by the recent 2011-2016



drought [Swain, 2015]. The drought began due to a combination of temperature and precipitation anomalies that reduced snowpack, spring runoff and inevitably soil moisture on agricultural fields [Luo et al., 2017]. This change in water availability resulted in reduced surface water supplies which led to a variety of drought adaptations, including increased groundwater pumping to meet irrigation demands.

During these record-breaking drought years, California’s reliance on groundwater increased from approximately 40% to 60% [DWR, 2013]. An evaluation of California’s groundwater basins found that 127 of the state’s 515 basins - accounting for 96% of the state’s total groundwater use - were at risk of overdraft [DWR, 2017]. Overdraft-associated impacts such as increased extraction costs, land subsidence, sea-water intrusion and water quality degradation, among others [DWR, 2017], created widespread alarm that culminated in the legislative passing of the Sustainable Groundwater Management Act (SGMA) of 2014. Until that point, groundwater pumping was largely unregulated and unmanaged, despite the existence of mechanisms for local management. Only 14% of water agencies had developed voluntary groundwater management plans before SGMA [MacLeod and Méndez-Barrientos, 2019]. Similarly, only 4% of groundwater basins had been adjudicated before SGMA (Wat. Code §10720.8.).

**3.2.3. The Sustainable Groundwater Management Act (SGMA).** SGMA is a top-down, state-mandated governance effort that requires local public agencies overlaying groundwater basins to formally organize through groundwater sustainability agencies (GSAs) and create groundwater sustainability plans (GSPs). The goal is to prevent future undesirable environmental impacts associated with groundwater overdraft [SGM, 2014]. SGMA provided substantial flexibility for groundwater users to form GSAs and did not grant any single existing agency jurisdiction or mandate a particular governance approach. It allowed any local public agency with water supply, water management, or land use responsibilities to be eligible to become a GSA (Wat. Code, § 10721, (j)), or form a collective GSA with other local agencies, bounded within the same groundwater basin(s) (Wat. Code §10723 (a)).

Disadvantaged communities (i.e. state-designated communities that are most impacted by economic, health, and environmental burdens [Commission, 2015]), independent farmers, and private pumpers not representing any local public agency (called hereby “independent groundwater

users”), could be formally included in the decision-making bodies of GSAs. However, GSA formation processes challenged the capacity of these groups to participate, requiring frequent attendance at meetings, enough technical knowledge to navigate legal and hydrological jargon, and the social influence and authority to adequately participate in decision-making [Méndez-Barrientos et al., 2019]. These unspoken requirements of participation created marked representation differences between local public agencies and independent groundwater users [Dobbin and Lubell, 2019]. For example, Méndez-Barrientos, Bostic and Lubell (2019) found that only 12% of GSAs have independent groundwater users as formal representatives on management boards.

**3.2.4. Farmer participation in SGMA.** Recent research has shown that while many farmers have felt underrepresented in the GSA development process [Niles and Wagner, 2017, Niles and Wagner, 2019], some have effectively pursued various strategies to ensure their interests are represented. One such strategy has been securing support from regional farmer organizations such as the Farm Bureau, which have more resources and staff that could participate in GSA meetings. In addition, some water and irrigation districts have advocated for the expansion of their jurisdictions by annexing land owned by independent groundwater users to facilitate representation from these groups [Conrad et al., 2018]. However, variance among levels of organization around land and water management and knowledge on water policy processes may challenge adequate participation of the wide diversity of farmers and farming systems that exist across California [Rudnick et al., 2016].

### 3.3. Methods

**3.3.1. Data collection.** We conducted 27 semi-structured interviews with farmers in four different groundwater basins (12 different sub-basins) across the state between 2016 and 2018. Farmers who had a connection to the boundary organizations University of California Cooperative Extension, the Farm Bureau and the USDA Natural Resources Conservation Service (NRCS) were contacted. The farmers interviewed were, in theory, more likely to be participating in SGMA processes because of their relationships with these boundary organizations, which typically diffuse information and connect various stakeholders to policy processes [Carr and Wilkinson, 2005, Cash, 2001, Klerkx et al., 2010]. These social network characteristics aside, interviewed farmers

TABLE 3.1. Agricultural operation characteristics from SGMA informational interviews with growers throughout California.

Characteristics	SGMA participant (n = 15)	Non-participant (n = 12)	Total sample (n = 27)
<b>Farmer characteristics</b>			
Organic operation	3 (20%)	5 (42%)	8 (30%)
Female farmers	2 (12%)	1 (8%)	3 (11%)
Farmer age >50 years	12 (80%)	10 (83%)	22 (81%)
Farming experience >30 years	8 (53%)	9 (75%)	17 (63%)
Mean farm size (acres)	4,586	2,206	3,344
<b>Crop type</b>			
Annual	2 (12%)	2 (16%)	4 (15%)
Perennial	10 (75%)	5 (42%)	15 (56%)
Mixed/multiple	3 (20%)	5 (42%)	8 (30%)
<b>Water access</b>			
Groundwater only	5 (33%)	4 (33%)	9 (33%)
Riparian surface water	2 (12%)	2 (16%)	4 (15%)
Water district water	8 (53%)	6 (50%)	14 (52%)
Both groundwater & surface water	7 (47%)	7 (58%)	14 (52%)

differed in geography and the characteristics of their farming businesses (i.e. farm size, crop type, water rights and membership to water service organizations) (Table 3.1). We did not select farmers based on their knowledge and involvement in SGMA. Instead, we selected farmers based on their location to ensure geographical representation throughout the state, ensuring we could capture diverse experiences related to precipitation distribution (e.g. North versus South Central Valley), groundwater basin overdraft and their access to water infrastructure (e.g. access to Central Valley project and irrigation/water district service).

Our semi-structured interviews were predominantly guided by two lines of questioning. First, we sought to determine knowledge of SGMA and awareness of the environmental impacts of groundwater overdraft. If the interviewees indicated positive knowledge of SGMA, then interviews sought to understand level of involvement in local GSA(s) and explore barriers to participation in the process. Interviews were subsequently transcribed, hand-coded and analyzed to understand what facilitated or prevented participation in groundwater governance. Member checking, which refers to the process of returning transcribed interviews to study participants for verification and correction [Birt et al., 2016], was not done with interviewees. Instead, authors hosted a focus group

discussion in the San Joaquin Valley (September 17th, 2019) and attended several GSA, SGMA farmer public meetings, and farm field days from 2016 to 2018.

In parallel, we collected publicly available secondary data to characterize farmer experience with environmental change, including annual precipitation, change in groundwater elevations during drought, and conditions of farmers' groundwater basins (Table 3.2). Using historical precipitation data from the California Irrigation Management Information System (CIMIS) database, we calculated precipitation changes for each farmer. The nearest CIMIS station to each farm was identified and for each station, the average annual precipitation was calculated for all available years. The calculated difference between the 20 or 30 year historical average (depending on data availability) and the 2011-2015 drought average was used to estimate experienced precipitation reduction. Using the Department of Water Resources (DWR) SGMA Data Viewer website, we calculated groundwater elevation changes for each farmer. The closest monitoring well to each farm was identified and for each well, water surface elevation (WSE) pre- and post-drought was extracted (late 2011 and late 2016-early 2017 depending on the well reading available). The calculated difference between pre and post-drought WSE was used to estimate each farmers' experience of groundwater level reduction. Additionally, we included the groundwater sub-basins and their given prioritization by the DWR where the interviewees' farms were located.

**3.3.2. Data analysis.** Semi-structured interviews were motivated by the literature on participation drivers in environmental governance processes previously discussed. As such, we used a theory-driven approach to develop a coding framework to analyze interviews.

Our analysis relied on two rounds of qualitative coding. First, we coded farmer and farm characteristics, and knowledge and participation in SGMA processes for all farmers. We built a database of descriptive variables for each interviewee, including the farm locations, water sources, farming experience, crop type, knowledge and participation in SGMA, and awareness of environmental impacts of groundwater overdraft. At this stage, we also integrated the secondary environmental change data, including annual precipitation and groundwater elevation changes, and the groundwater basin and its prioritization where the farmer was located.

Our second round of interview coding focused on identifying the drivers of SGMA participation. We prioritized the farmers that were knowledgeable of SGMA in order to understand why they

TABLE 3.2. Environmental change perceptions and experiences from SGMA informational interviews with growers throughout California.

Variables	SGMA participant (n = 15)	Non-participant (n = 12)	Total sample (n = 27)
Experienced previous CA droughts	13 (87%)	10 (83%)	23 (85%)
<b>SGMA basin status</b>			
In High Priority Basins	12 (80%)	12 (100%)	24 (89%)
In Medium Priority Basins	3 (20%)	0	3 (11%)
<b>Awareness of overdraft-associated impacts</b>			
Reduced surface water allocations	3 (20%)	6 (33%)	9 (33%)
Lost aquifer storage	0	1 (8%)	1 (4%)
Reduction in GW quality	4 (27%)	2 (17%)	14 (52%)
Seawater intrusion	1 (7%)	1 (8%)	2 (7%)
Land subsidence	3 (20%)	1 (8%)	4 (15%)
Lowering GW levels	9 (60%)	7 (58%)	16 (60%)
<b>Surface and groundwater reductions</b>			
Mean reduction in precipitation during drought relative to historic average*	23%	29%	26%
Mean reduction in groundwater level (WSE) during drought (ft)**	30.7	43.1	36.6

\* Reduction in precipitation calculated by finding average local precipitation during drought years (2011-2016) for each farmer (from nearest CIMIS station) and comparing to 20 or 30 year historic average precipitation levels at their local station.

\*\* Reduction in groundwater level calculated by finding closest monitoring well to each farmer's location and evaluating Water Surface Elevation (WSE) (measured in feet) before drought (2010-2011) and end of drought (late 2016), and calculating difference in groundwater level. Greater numbers indicate a greater depression in groundwater levels (monitoring well level data available from SGMA Data Viewer).

were or were not participating, and what factors motivated their engagement. Interview excerpts on participation were extracted and organized by key themes, revealing the underlying behavioral drivers and motivations of participation that we discuss in depth in the following section.

**3.3.3. Limitations.** This research has several limitations that should be noted. First, although interviewed farmers reflected crop type and mirrored demographic trends seen in the state's agricultural census, the farm size, farm and farmer diversity, and location of farmers primarily located in high priority basins, does not sufficiently represent the diversity of California agriculture and farmers' roles under SGMA. In addition, nearly all interviewed farmers were fairly well-connected to traditional information networks, as those same networks facilitated the research team's introductions to interviewees. Lastly, though we interviewed four farmers with less than 100

acres (and an additional four with less than 500 acres), we also interviewed a few farmers with very large operations (+10,000 acres), and thus the mean farm size of our sample is much larger than the mean farm size across California. Despite these limitations, we believe our findings contribute an important and nuanced discussion on the diversity of agriculture that will be affected by the recent passage of SGMA and ongoing GSP development process.

### 3.4. Results and discussion

Our interview analysis yielded four key findings that we discuss in depth in this section. First, leveraging existing, surface water, social networks [Bolding, 2004, Wester, 2008] to develop groundwater management agencies facilitated participation from farmers who were embedded in those networks, but limited participation from independent groundwater users. Second, access to political, social, economic, natural, and human resources [Ribot and Peluso, 2003] facilitated the participation of some types of farmers - namely large, industrial, surface-water rights holders. Third, all interviewed SGMA participants shared a collective identity [Abers, 2007] framed as an aversion to state control which motivated their participation in local policy discussions that they may have otherwise ignored. Finally, nearly all interviewed farmers recognized how both short- and long-term environmental changes had altered their water access, though this did not stand out as a factor that motivated SGMA participation (Table 3.2).

**3.4.1. Environmental change experiences of interviewed farmers.** We interviewed 27 farmers across California (Figure 3.1). Just over half of our interviews (n=15) were with farmers who were participating in SGMA (henceforth “SGMA participants”) to some degree, either by attending local meetings for their GSAs (n=9) or serving as a GSA Board Member (n=6). The remaining 12 interviews were with farmers who were not participating in SGMA (referred to as “Non-participants”). Only two farmers had not heard of SGMA at all.

Nearly all farmers interviewed (23 out of 27) had previously experienced a drought in California. The 2011-2016 drought led to reductions in average annual precipitation for all farmers interviewed, with an average decrease of 26% from “normal” (long-run historic averages) precipitation. As noted previously, reduced surface water availability spurred a dramatic increase in groundwater extraction, noticeably lowering aquifer levels over the course of a few years; on average, interviewees experienced

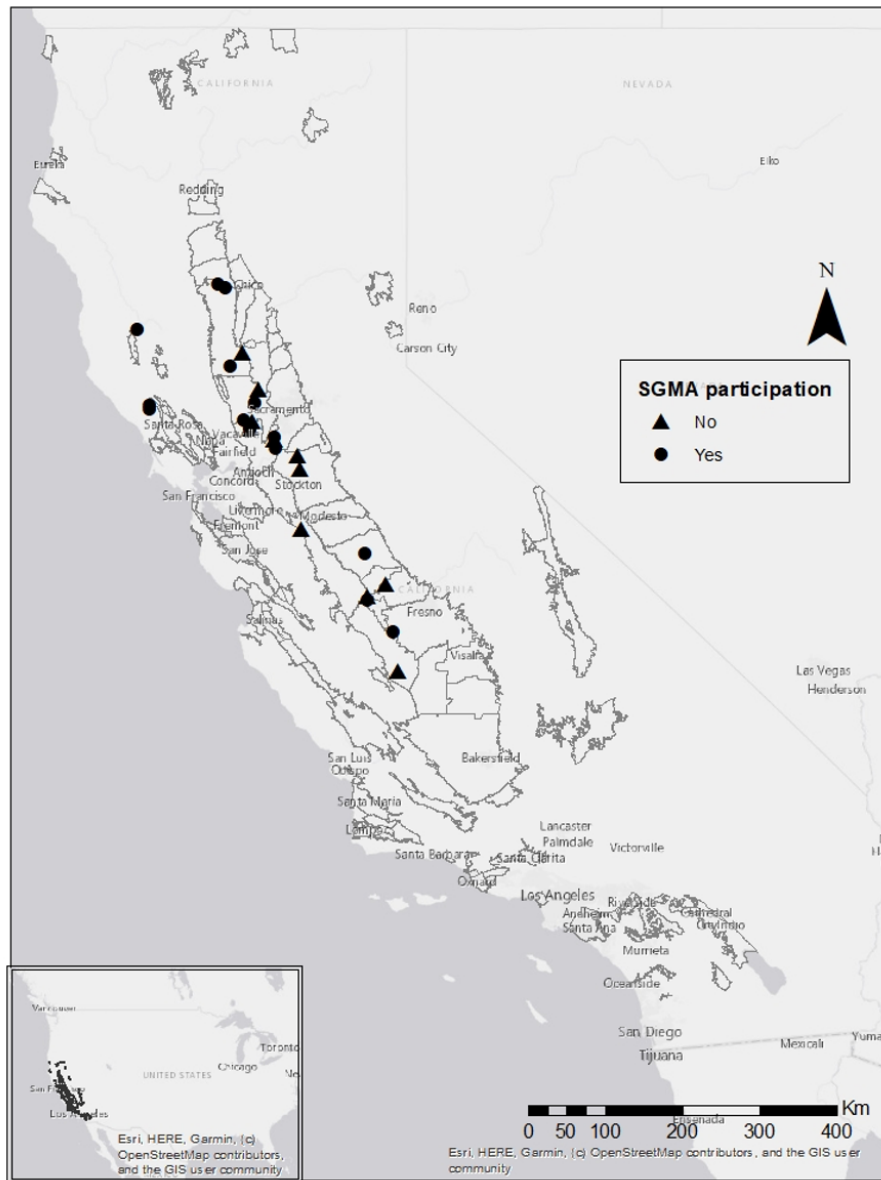


FIGURE 3.1. Distribution of interviewees across groundwater basins in California.

a decrease of 36.6 feet in Water Surface Elevation (WSE) (Table 2). We found no notable differences between SGMA participants and non-participants, and their experienced precipitation reductions or groundwater level changes, suggesting that these short-term physical changes were not a driver of participation.

To gauge experiences with longer term groundwater changes, we asked farmers about their experiences related to groundwater overdraft environmental impacts. We found mixed responses (Table 2). Only one farmer mentioned loss of aquifer storage, two farmers mentioned sea-water intrusion (a phenomenon exclusive to coastal areas), four mentioned land subsidence, six mentioned reductions in groundwater quality, and nine mentioned reduced surface water allocations. The most frequently mentioned environmental impact was lowering of groundwater levels, with 60% (n=16) of interviewees expressing great related concern. Ten farmers reported that they experienced a combination of various environmental impacts related to groundwater overdraft. Notably, the recognition of these undesirable impacts was similar for SGMA participants and non-participants. Moreover, exactly half of the farmers who were in high priority basins participated in SGMA (12 out of 24), though all of the farmers in medium priority basins participated (3 out of 3).

**3.4.2. Leveraging existing social networks to assert local control.** Our interview data shows a clear distinction between the political access enjoyed by some farmers, based on their membership to existing social networks around water management (i.e. irrigation and water districts), compared to the restricted access granted to independent groundwater users. SGMA's statutes (Wat. Code, § 10721, (j) and Wat. Code §10723 (a)) effectively granted authority to existing public agencies by stipulating that only public agencies could become a GSA, or form a GSA with other public agencies overlaying a groundwater basin. This automatically limited participation to a subset of stakeholders: independent groundwater users, such as disadvantaged communities, farmers and private pumpers unaffiliated to any local public agency.

Among the farming community, this created a governance paradox. Farmers who were affiliated with public agencies due to their surface water rights were granted authority to have formal representation or form a GSA; meanwhile, farmers who were entirely groundwater-dependent users and had not historically organized in public agencies due to the private hydraulic nature of groundwater (i.e. through wells), were denied that access. In essence, groundwater users who exclusively depended on this resource were at a disadvantage to participate and gain representation in SGMA, a groundwater reform that was meant to protect them.

This disadvantaged situation for independent groundwater users meant that they had two options to participate in SGMA: either organize to collectively form a new public agency and



formally become a GSA, or be incorporated into an existing GSA decision-making board. The high transaction costs of pursuing both initiatives at the same time meant that few groups were successful in achieving either strategy. For example, of the 261 GSAs that were formed with SGMA, 47 (18%) were exclusive single GSAs constituted by farmer-led public agencies such as irrigation and reclamation districts. None (of the 261 GSAs) were constituted by recently formed public agencies of unorganized independent groundwater users. Furthermore, only 31 of the 261 GSAs (12%) had independent groundwater users as voting representatives in GSAs management boards [**Méndez-Barrientos et al., 2019**]. These limitations disproportionately impacted the representation of small farmers and disadvantaged communities, suggesting that SGMA, whether intentionally or not, enabled the participation of public agencies within existing hydrosocial networks [**Bolding, 2004, Wester, 2008**], while keeping independent groundwater users outside of decision-making boards, largely unrepresented.

Our interviews illustrated the lengths to which independent groundwater users went to ensure some level of participation in SGMA. For example, one group of farmers in the North Coast hydrologic region revived a water district that was no longer functioning to be able to have formal representation in one GSA where leaders opposed inclusion of non-public agency representatives (pers. comm. CF11). Similarly, a group of groundwater users in the Sacramento Valley formed a group to advocate and negotiate for a voting seat within the new GSA's management board, but were unable to formalize their legal status as a public agency within the time frame of the GSA formation process (pers. comm. CF12).

Additionally, our interview data with SGMA participants exposed the significant representation demand disparities, both in time and money, between public agency representatives and independent groundwater users. Bi-weekly and sometimes weekly meetings for each GSA were challenging for farmers, especially for those who did not have staff or other representatives that could attend on their behalf. In contrast, representatives and staff from public agencies and organized farm groups (e.g. county and city officials, water and irrigation districts representatives and Farm Bureau staff) were paid to be there [**de Loë et al., 2015, Holley, 2010**]; SGMA became part of their job and paid responsibilities. In addition, farmers whose farms were located in basins with multiple GSAs, or who had extensive land that stretched across multiple groundwater basins, had

to attend SGMA meetings for more than one GSA, which was more costly and time-consuming (pers. comm. CF8, CF11, CF12, CF20, CF22). SGMA processes thus presented asymmetrical transaction costs [Libecap, 1994] for various stakeholders.

Furthermore, multi-sector and multi-actor heterogeneity increased deliberation time and raised questions on adequate representation. Conflicting priorities (e.g. utilities interested in long-term resource access versus farmers focused on flexibility and short-term use) increased deliberation time to an already demanding process [Ayres et al., 2017]. Rudnick et al. (2016), who calculated agricultural diversity by farm size and farm income in California, demonstrated the various representation needs of the agricultural sector. One agricultural stakeholder raised this precise conflict: “Say you want to allow an ag[ricultural] seat or a residential seat [on a GSA board of directors], how do you pick that person?...[If] there’s no special district of agriculturalists, do you let the Farm Bureau pick [?], but then that may be politically more conservative than The Community Alliance of Family Farmers...” (pers. comm. RCD1).

**3.4.3. The political economy of groundwater that enables access to environmental governance.** To further understand the political, economic and organizational disadvantage of groundwater users compared to surface water irrigators, it is worth noting that the state of California emerged through the most elaborate hydraulic (surface water) systems in the world’s history. Since the 1887 Wright Act and with support from the federal Bureau of Reclamation and the State, corporate irrigation enterprises and (white) farmers organized in irrigation districts, have built expansive irrigation works for surface water delivery [Worster, 1982]. Since then, surface water irrigators have organized around districts not only to distribute water for canal irrigation and manage water rights, but more importantly, to mediate their political interests at higher government levels [Mollinga, 2003].

In contrast, independent groundwater users, who have historically not organized in districts, have not directly benefited from state nor federal government funding. As it was mentioned before, farmers who exclusively rely on groundwater have instead invested in private hydraulic property (i.e. wells) with little interaction among themselves or with public agencies regarding water supply. These contrasting histories have resulted in the expansion of irrigation districts and other types

of surface water districts serving California’s large industrial farmers, juxtaposed with fragmented operations of unorganized groundwater users.

One farmer described how regions with public agencies had a much easier time encouraging farmer participation than areas with no formally-organized farming groups: “The last [meeting] I went to for a San Joaquin GSA, there were 450 [farmers].... Now, when I go to the East side GSA [with no organized districts], there [were] only 3 people. Because we don’t have a vote, a lot of people don’t show up. We’re not part of an irrigation system or a city so they call us the white area” (pers. comm. CF7). Lack of clarity on how unorganized, independent groundwater users would be represented, or if they would have any voting representation at all, appears to have further discouraged participation from these farmers.

For some small-scale immigrant farmers, language, culture and land ownership barriers may have further hindered access to existing social networks of public agencies that facilitated participation in SGMA processes. Immigrant and refugee farmers such as Latino, Hmong and other Southeast Asian farmers in the Central Valley are mostly tenants, operating with short-term land leases. Since land ownership is key to having access to loans, these farmers also have limited access to financial resources to drill new wells when groundwater levels drop. As such, they are particularly vulnerable to changes in groundwater levels [**Dahlquist-Willard et al., 2016, Shah et al., 2007**]. To cope with limited access to SGMA processes, the Asian Business Institute and Resource Center (ABIRC) and the University of California Cooperative Extension has been working with some GSAs to engage small-scale disadvantaged farmers in GSA decision-making processes. However, with so many GSAs throughout the Central Valley, it has been difficult for non-profit groups or extension personnel to facilitate the inclusion of various independent groundwater user groups in groundwater governance agencies and processes.

It is noteworthy that the average farm size of SGMA participants (4,586 acres) was substantially larger (by 52%) than that of non-participants (2,206 acres) in our sample (Table 1). This result is even more striking when compared to the average California farm size (fluctuates between 300-400 acres, depending on year) [**CDEA, 2016**] given that the average size of our full sample (3,344 acres) is significantly greater. Farm size can serve as a proxy to access to capital and labor, and

therefore ability to overcome the transaction costs of SGMA participation and representation in GSAs throughout the state.

Access to capital was especially important in SGMA processes because formal representation had a ‘price-tag’ per voting seat in some GSAs. This meant that in order to gain official representation at a board of directors, public agencies and sometimes independent groundwater users, had to contribute financially to ensure voting rights in GSAs boards [Méndez-Barrientos et al., 2019]. These high upfront costs further challenged inclusion of independent groundwater users in many GSAs, who in the absence of their own organized hydrosocial networks [Bolding, 2004, Wester, 2008], faced more barriers to secure financial contributions. In contrast, irrigation and water districts could rely on their collective membership and their operational budgets to appropriate funds to formally participate in GSAs. Participating in SGMA thus became prohibitive for stakeholders with less resources [Lubell et al., 2002].

**3.4.4. Defining a “common enemy”:** **Aversion to state control.** Our interviews revealed a consistent discourse among farmers: tension between central and local control over groundwater management. This was unanimously underscored in interviews with SGMA participants as an important participation driver, alluding to a strong collective identity on this issue [Abers, 2007].

The resistance toward state intervention appeared twofold. First, there was a shared perception that blanket regulations implemented in a top-down fashion fail to recognize important local differences. As a result, farmers were motivated to be involved in the formation of GSAs out of self-preservation. As one farmer puts it, “Such a uniform regulation state-wide wouldn’t necessarily work, so we were against SGMA. But, I saw the inevitability of the law being passed. [Therefore] I strongly advocated that [our] agricultural community should form. . . some kind of organization that should be qualified to be GSA eligible” (pers. comm. CF11). Second, multiple farmers emphasized that agriculture is continually facing more regulatory pressures, and SGMA may just be the newest in a sequence of environmental regulations. For example, another farmer shared, “...it’s another way to take farming out. It’s been a lot...Fish, water supply, water quality. And those were all surface. If you [had] groundwater, you were kind of safe, and you could be a farmer and

be safe. And now you're not. So at what point do they [the state] feel like they just don't want farming anymore?" (pers. comm. CF21).

With these two fears in mind, some farmers participated in SGMA to avoid further state intervention and maintain local control. This finding is consistent with research that suggests aversion to government intervention is an explicit motivator for farmers to participate in local governance processes [**Hardy and Koontz, 2010, Stock et al., 2014, Taylor and Van Grieken, 2015**]. In addition, this motivation may have important implications for the design of collective-action rules. Aversion to state-control could translate to the preservation of the status-quo in the design of new management rules, as a way to keep government out.

### 3.5. Conclusions

We set out to understand what motivated farmers to participate in environmental governance processes using the implementation of SGMA, a groundwater reform currently underway in California, as a case study. Drawing from secondary and qualitative interview data from 27 farmers across the state, we find that socio-institutional rather than environmental change variables, explain participation and representation in groundwater governance processes. Contrary to the literature on environmental behavior [**Sanderson and Curtis, 2016, Weber and Stern, 2011**], we do not find that environmental experiences are a consistent driver of farmer participation in groundwater governance processes; both short- and long-term experience with environmental changes appeared to have no influence. This concurs with observed farmer behavior in the latest drought which showed that amidst surface water scarcity, those who could afford it increased and expanded their use of groundwater. Nevertheless, it would be interesting to explore if environmental change is more likely to explain participation on groundwater governance amongst farmers with less resources. They may be less concerned with government intervention [**Niles et al., 2013**] and more motivated to regulate groundwater given that they are more vulnerable to changes in groundwater levels [**Dahlquist-Willard et al., 2016, Shah et al., 2007**].

Using the framework presented by Hoogesteger and Wester (2015) to organize analysis of results, we found that existing social networks around water management largely explain participation in groundwater governance processes in California. Farmers who were participating in SGMA were

more likely to have associations to local public agencies as members or representatives of those agencies themselves. This is not coincidental since SGMA built the implementation of its institutional reform around existing public agencies, who successfully adapted their spatial, social, institutional and material reach from surface to groundwater governance. This remarkable institutional capture illustrates the durability and strength of surface water public agencies in California [Bolding, 2004].

This case study also supported previous findings that have shown that access to resources [Ribot and Peluso, 2003], which in turn enables farmers to overcome transaction costs [Libecap, 1994, Ostrom, 1990], is key to participation in policy processes. We found that farmers with larger land acreages, with greater financial and human capital, and even English language skills, might have more agency to participate in SGMA processes and are likely better represented in GSAs throughout the state.

This has potential negative implications for the farmers who qualify as independent groundwater users (i.e. are not members of irrigation or water districts, which as public agencies are eligible to participate in SGMA). These independent pumpers are likely to have relatively less social and political capital that surface water users have historically developed [Worster, 1982], cannot afford to contribute financially as individuals to formally participate in GSA decision-making boards, and cannot afford the time required to attend multiple, recurrent GSA meetings [Ayres et al., 2017, Dahlquist-Willard et al., 2016, Holley, 2010, Shah et al., 2007]. As a result, whether intentionally or not, SGMA has facilitated the participation of well-organized and well-resourced farmers, excluding less-organized and less-resourced farmers. If GSAs do not make a concerted effort to support participation from independent groundwater users, the institutional process will likely limit governance discussions to the interests of represented groups, which among the farming sector appears to exclude small farmers.

In addition, our findings concord with existing literature on farmer participation in collaborative environmental governance [de Loë et al., 2015, Ferreyra et al., 2008, Hardy and Koontz, 2010, Niles et al., 2013, Stock et al., 2014, Taylor and Van Grieken, 2015], which have found that aversion to state control and government intervention is an instrumental participation driver for farmers. This has important implications for policy implementation. First, state aversion

may encourage attempts to make local collaboration ‘appear’ successful in order to avoid state intervention. With this priority in mind, stakeholders may focus on meeting deadlines and minimum requirements, excluding diverse voices that may vocalize dissent, delay processes or try to negotiate decisions. In turn, this may end up diverting needed state attention in areas that otherwise mask high conflict, and unequal participation and representation in decision-making boards. This defensiveness against government can thus render in the preservation of the status-quo. Opposition to state-led institutional change could deter the creation of more ambitious operational and collective-action rules [**Ostrom, 1990**].

The California case study clearly illustrates that the strength of existing (surface water) hydrosocial networks [**Bolding, 2004, Wester, 2008**] in combination with resource disparity within communities [**Agrawal and Gibson, 1999, Ribot and Peluso, 2003**] that cannot afford the high transaction costs of participation [**Libecap, 1994, Ostrom, 1990**], and the preservation of the status-quo that results from a collective identity [**Abers, 2007**] against governmental intervention [**de Loë et al., 2015, Ferreyra et al., 2008, Hardy and Koontz, 2010, Niles et al., 2013, Stock et al., 2014, Taylor and Van Grieken, 2015**] can lead to unequal representation from groundwater-dependent users in the very agencies that have supposedly been developed to protect them. Without adequate representation in groundwater governance processes, the fate of small-scale and historically disadvantaged farmers remains uncertain as new environmental reforms are implemented. Unfortunately, this reality is prevalent [**Shah et al., 2007**] and continues to challenge assumptions of the widely used collaborative governance approach for common-pool resource (CPR) management [**Agrawal and Bauer, 2005, Bryson et al., 2006, O’Toole Jr and Meier, 2004**]. We offer these insights on farmer participation in groundwater management processes to shed light on potential shortcomings of CPR governance reforms and improve the design of future environmental governance processes that seek farmer participation.

## Conclusive Remarks

Sustainable agricultural water management in a changing climate requires a coupled understanding of human and natural systems involved in resource management from a range of temporal and spatial scales, across climates, and between production systems. This research sought to develop this coupled understanding to answer the question:

*How can farmers maintain food production under a changing climate while reducing their water use?*

Answering this question involved bridging hydrologic, agronomic, and social sciences to study California farms and their hydrologic systems. This dissertation explored agricultural water management at three increasingly larger scales of demand-side management strategies. It first focused on a single field of farm land, then looked at an entire farming operation, and finally zoomed out to study farmer decision-making across the state. Although the chapters focused on individual scales, they each include farmers in scientific monitoring and evaluation to ensure relevant and applicable research results.

Each chapter uniquely contributes to the understanding of sustainable agricultural water management, simultaneously offering practical information for farmers under climatic and regulatory pressures and highlighting future avenues of inquiry. Chapter 1 describes how winter cover crops affect soil moisture and evapotranspiration on commercial production farms through a 3-year agricultural field data collection campaign. This work focuses on two components of the water budget for Central Valley farmland that is used to grow processing tomatoes and almonds, but this approach can be expanded to other commodities and parts of the state. Chapter 2 monetizes the costs and benefits associated with winter cover cropping by supplementing a literature review with farmer interviews to construct a net-present value model. This chapter provides the first economic evaluation of winter cover cropping in California and lays the groundwork for applying the methodology



to other cropping systems and locations, even beyond California's specialty crops. And Chapter 3 identifies drivers that motivate farmers' participation in groundwater governance processes by coupling farmer interviews with the hydrologic characterization of environmental changes experienced by farmers. By highlighting potential shortcomings of new groundwater management legislation in California, the research points to the need for future exploration of farmer involvement in off-farm common-pool resource management.

Together, these three chapters offer practical information for California's agricultural community to adapt to a hydrologic landscape that is increasingly variable and under increasing scrutiny due to climate change and environmental regulations. This research suggests that sustainable agriculture practices that improve soil health and sequester carbon can be adopted by specialty crop farmers and contribute to a more resilient future for California agriculture. Farmers need long-term planning horizons, willingness to be farming their land year-round, and could greatly benefit from financial incentives if policy makers attribute higher value to climate change mitigation practices. Such a resilient future is likely possible if these individual management practices are adopted at a large scale across the state and are implemented in coordination with local water resource management policies, such as SGMA, and local actors, such as farmers and ranchers.

California's water management challenges represent an important component of the global challenge to maintain food production under climatic and regulatory pressure. Results from applied research in this region, which are included in this dissertation, provide insights relevant to agricultural systems in arid regions around the world. This applied research also showcases the value of using farmer needs to inform the design of physical science-based experiments for developing adaptable and scalable water management strategies and practices. Such research contributes to the coupled understanding of human and environmental systems, which is necessary to ensure the viability of farming, the ecosystems it depends on, and economies and communities it supports.

## APPENDIX A

### Appendix

#### A.1. Evapotranspiration collection and analysis details

TABLE A.1. Description of the dates of evapotranspiration data collection and corresponding analysis techniques.

Year	Site	Treatment	Analysis	Program	Start date	End date
2017	Davis	Fallow	SR	Lite	1/28/17	3/9/17
2017	Davis	Cover	SR	Lite	1/28/17	3/14/17
2017	Five Points	Cover	SR	Lite	2/14/17	3/5/17
2017	Five Points	Fallow	SR	Lite	2/15/17	3/5/17
2018	Davis	Cover	SR	Lite	11/7/17	2/6/18
2018	Davis	Cover	SREC	Full	2/10/18	2/22/18
2018	Davis	Fallow	SR	Lite	11/7/17	2/8/18
2018	Davis	Fallow	SREC	Full	2/10/18	2/22/18
2018	Five Points	Fallow	SR	Lite	11/15/18	2/14/18
2018	Five Points	Fallow	SREC	Full	2/22/18	4/2/18
2018	Five Points	Cover	SR	Lite	11/15/18	2/14/18
2018	Five Points	Cover	SREC	Full	2/16/18	4/2/18

#### A.2. Weekly evapotranspiration data

TABLE A.2. Calculated weekly values used in the evapotranspiration analysis. Tables values include site, treatment (Tmt), station (Stn), year (Yr), week (Wk), date, reference evapotranspiration ( $ET_o$ ), actual evapotranspiration ( $ET_a$ ), precipitation (Pcp), crop coefficient ( $K_a$ ), and cumulative actual evapotranspiration (Cum $ET_a$ ).  $ET_o$ ,  $ET_a$ , Pcp, and Cum $ET_a$  all reported in millimeters.

Site	Tmt	Stn	Yr	Wk	Date	$ET_o$	$ET_a$	Pcp	$K_a$	Cum $ET_o$
Davis	fallow	CC1	1	1	2/3/17	8.66	3.78	54.2	0.44	3.78
Davis	fallow	CC1	1	2	2/10/17	5.37	2.21	63.1	0.41	5.99
Davis	fallow	CC1	1	3	2/17/17	13.41	8.92	31.8	0.67	14.91

Davis	fallow	CC1	1	4	2/24/17	10.37	4.09	45.2	0.39	19.01
Davis	fallow	CC1	1	5	3/3/17	18	10.34	0	0.57	29.35
Davis	fallow	CC1	1	6	3/10/17	15.47	9.28	10.3	0.6	38.63
Davis	cover	CC2	1	1	2/3/17	8.66	2.42	54.2	0.28	2.42
Davis	cover	CC2	1	2	2/10/17	5.37	1.8	63.1	0.33	4.22
Davis	cover	CC2	1	3	2/17/17	13.41	5.06	31.8	0.38	9.28
Davis	cover	CC2	1	4	2/24/17	10.37	2.96	45.2	0.29	12.24
Davis	cover	CC2	1	5	3/3/17	18	5.96	0	0.33	18.2
Davis	cover	CC2	1	6	3/10/17	15.47	7.09	10.3	0.46	25.29
Davis	fallow	CC2	2	1	11/13/17	9.2	4.8	0.2	0.52	4.8
Davis	fallow	CC2	2	2	11/20/17	7.6	6.2	23.7	0.81	11
Davis	fallow	CC2	2	3	11/27/17	6.5	3	3.2	0.47	14
Davis	fallow	CC2	2	4	12/4/17	11.2	2.6	0	0.24	16.6
Davis	fallow	CC2	2	5	12/11/17	11.2	0.5	0	0.04	17.1
Davis	fallow	CC2	2	6	12/18/17	11.7	1.4	0	0.12	18.5
Davis	fallow	CC2	2	7	12/25/17	7.9	0.9	0.7	0.12	19.4
Davis	fallow	CC2	2	8	1/1/18	8.2	1.3	0	0.16	20.7
Davis	fallow	CC2	2	9	1/8/18	3.7	2.9	73.6	0.79	23.6
Davis	fallow	CC2	2	10	1/15/18	3.9	5.1	12.7	1.32	28.7
Davis	fallow	CC2	2	11	1/22/18	5.3	5	3.2	0.95	33.7
Davis	fallow	CC2	2	12	1/29/18	7.7	6.4	7.5	0.84	40.1
Davis	fallow	CC2	2	13	2/5/18	13.7	6.6	0.2	0.48	46.7
Davis	fallow	CC2	2	14	2/12/18	19.6	9.2	0	0.47	55.9
Davis	fallow	CC2	2	15	2/19/18	21.5	7.5	0.2	0.35	63.4
Davis	cover	CC1	2	1	11/13/17	9.2	4.4	0.2	0.48	4.4
Davis	cover	CC1	2	2	11/20/17	7.6	4.7	23.7	0.62	9.1
Davis	cover	CC1	2	3	11/27/17	6.5	2.9	3.2	0.45	12
Davis	cover	CC1	2	4	12/4/17	11.2	2.3	0	0.21	14.3

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Davis	cover	CC1	2	5	12/11/17	11.2	1.3	0	0.12	15.6
Davis	cover	CC1	2	6	12/18/17	11.7	3	0	0.25	18.6
Davis	cover	CC1	2	7	12/25/17	7.9	1.2	0.7	0.16	19.8
Davis	cover	CC1	2	8	1/1/18	8.2	2.7	0	0.33	22.5
Davis	cover	CC1	2	9	1/8/18	3.7	2	73.6	0.54	24.5
Davis	cover	CC1	2	10	1/15/18	3.9	3.7	12.7	0.95	28.2
Davis	cover	CC1	2	11	1/22/18	5.3	2.8	3.2	0.52	31
Davis	cover	CC1	2	12	1/29/18	7.7	4.4	7.5	0.57	35.4
Davis	cover	CC1	2	13	2/5/18	13.7	9.7	0.2	0.71	45.1
Davis	cover	CC1	2	14	2/12/18	19.6	14	0	0.71	59.1
Davis	cover	CC1	2	15	2/19/18	21.5	7.5	0.2	0.35	66.6
Five Points	fallow	CC4	1	1	2/21/17	11.02	12	28.4	1.09	12
Five Points	fallow	CC4	1	2	2/28/17	15.55	5.01	0.6	0.32	17.02
Five Points	fallow	CC4	1	3	3/7/17	16.11	5.66	0.1	0.35	22.68
Five Points	cover	CC3	1	1	2/21/17	11.02	13.31	28.4	1.21	13.31
Five Points	cover	CC3	1	2	2/28/17	15.55	9.48	0.6	0.61	22.79
Five Points	cover	CC3	1	3	3/7/17	16.11	9.64	0.1	0.6	32.43
Five Points	fallow	CC3	2	1	11/21/17	14.52	4.88	2	0.34	4.88
Five Points	fallow	CC3	2	2	11/28/17	15.67	4.89	2.8	0.31	9.76
Five Points	fallow	CC3	2	3	12/5/17	14.2	1.14	0	0.08	10.9
Five Points	fallow	CC3	2	4	12/12/17	12.23	1.99	0	0.16	12.9
Five Points	fallow	CC3	2	5	12/19/17	14.39	1.66	0	0.12	14.55
Five Points	fallow	CC3	2	6	12/26/17	10.33	2.22	1.2	0.22	16.77
Five Points	fallow	CC3	2	7	1/2/18	10.63	3.26	0	0.31	20.04
Five Points	fallow	CC3	2	8	1/9/18	8.42	3.92	NA	0.47	23.95
Five Points	fallow	CC3	2	9	1/16/18	4.54	2.53	0.7	0.56	26.48
Five Points	fallow	CC3	2	10	1/23/18	8.04	2.25	2	0.28	28.73
Five Points	fallow	CC3	2	11	1/30/18	9.68	5.22	2.7	0.54	33.95

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Five Points	fallow	CC3	2	12	2/6/18	15.89	6.93	0	0.44	40.89
Five Points	fallow	CC3	2	13	2/13/18	22.59	5.41	0	0.24	46.3
Five Points	fallow	CC3	2	14	2/20/18	21.89	2.97	NA	0.14	49.27
Five Points	fallow	CC3	2	15	2/27/18	18.57	2.47	1.4	0.13	51.74
Five Points	fallow	CC3	2	16	3/6/18	17.09	6.97	12	0.41	58.71
Five Points	fallow	CC3	2	17	3/13/18	21.62	10.59	10.6	0.49	69.3
Five Points	fallow	CC3	2	18	3/20/18	17.73	9.1	15.5	0.51	78.41
Five Points	fallow	CC3	2	19	3/27/18	22.18	12.79	34	0.58	91.19
Five Points	fallow	CC3	2	20	4/3/18	35.18	17.67	0	0.5	108.86
Five Points	cover	CC4	2	1	11/21/17	14.52	5.61	2	0.39	5.61
Five Points	cover	CC4	2	2	11/28/17	15.67	6.47	2.8	0.41	12.08
Five Points	cover	CC4	2	3	12/5/17	14.2	3.26	0	0.23	15.34
Five Points	cover	CC4	2	4	12/12/17	12.23	3.78	0	0.31	19.12
Five Points	cover	CC4	2	5	12/19/17	14.39	3.74	0	0.26	22.86
Five Points	cover	CC4	2	6	12/26/17	10.33	3.79	1.2	0.37	26.65
Five Points	cover	CC4	2	7	1/2/18	10.63	5.24	0	0.49	31.89
Five Points	cover	CC4	2	8	1/9/18	8.42	6.22	NA	0.74	38.11
Five Points	cover	CC4	2	9	1/16/18	4.54	3.49	0.7	0.77	41.6
Five Points	cover	CC4	2	10	1/23/18	8.04	2.89	2	0.36	44.49
Five Points	cover	CC4	2	11	1/30/18	9.68	5.17	2.7	0.53	49.66
Five Points	cover	CC4	2	12	2/6/18	15.89	8.04	0	0.51	57.7
Five Points	cover	CC4	2	13	2/13/18	20.19	6.04	0	0.3	63.75
Five Points	cover	CC4	2	14	2/20/18	19.1	3.71	0.93	0.19	67.46

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### A.3. Monetary values used in net present value models

A majority of the values described below are taken from the University of California Cost and Return studies for processing tomatoes in a crop rotation and an almond orchard [**Duncan et al.**,

**2016, Turini et al., 2018**]. Winter cover crops were estimated to be seeded on 100% of acreage for tomatoes fields and to cover 75% of possible acreage in almond orchards. All of the values described below were used to calculate the final values that were incorporated into a 10- or 30- year analysis, with all values discounted to the present value.

Direct costs were identical for every year of the analysis for processing tomatoes but varied for the almonds based on the year and what type of cover crop was being grown (annual vs. perennial). Seed costs were based on conversations with farmers, extension specialists and seed company representatives. The range in price describes the variety of potential seed mixes that are commonly used to winter cover crop in California's Central Valley and reflect seed mixes commonly used in annual and perennial systems. The mix for tomato operations was assumed to be a small grain forage mix (i.e. bell beans, winter peas, common vetch) purchased for \$0.40-0.75 per lb. and planted at a rate of 60-120 lbs. per acre. The mix for almonds was assumed to be a more expensive clover mix purchased for \$1.00-2.15 per lb. and planted at a lower rate of 20-40 lbs. per acre.

We assumed that planting and terminating winter cover crops only incurs labor costs. We estimated a farm worker would be paid a wage for machine labor and used wages from the Cost and Return studies. We assumed that this wage stays constant through the planning horizon. Planting labor costs were estimated to vary between 30 minutes to 1 hour of wages for a farm laborer running a machine [**Pratt et al., 2014**], valued at \$19.21 per hour for tomatoes and \$20.51 per hour for almonds. Seed and planting costs were realized every year for tomatoes but only during the first 4 years of the almond operation. Termination (i.e. killing and incorporating winter cover crops) labor costs were estimated to be double that of planting for the entire tomato timeline and the first 3 years of the almond operation. Beginning in the fourth year for the almond operation, labor costs for termination were estimated to be 2-4 mows per season, valued at \$15-25 per pass [**Pratt et al., 2014**].

Indirect costs were variable from year to year. We assumed that cover crops can complicate harvests of cash crops during the summer, as explained in the main text. Tomato growers risk delays in the emergence of tomatoes that could interfere with pre-determined weekly sales to tomato canneries, while almond growers may experience complications due to the presence of vegetation between tree rows that can interfere with hull harvest. The harvest complications were valued

as revenue losses. Informed by grower interviews, we estimated the risk exposure of contractual noncompliance with tomato canneries between 5 and 30% of annual yield every 5 years. We assumed that once every five years there could be a late winter rain that complicates cover crop termination and leads to delayed planting. The risk exposure of harvest complications in almond orchards was estimated to be half that. Revenue losses were calculated based on data from the Cost and Return studies. We estimated returns of \$55.50-85.50 per ton of tomatoes and \$2.62 per lb. of almonds, and yield ranges of 43-73 tons per acre for tomatoes and 1,000-3,400 lbs. per acre for almonds after year 6 (during full production). The yield ranges for almonds increase incrementally beginning in the third year.

Other indirect costs include depreciation of equipment and the opportunity cost of time spent learning how to cover crop. Equipment will depreciate more quickly if it is being used to cover crop in the winter, when it would otherwise be dormant. The depreciation costs were estimated to vary from 5 to 30% of annual capital recovery costs for equipment detailed in Cost and Return studies, \$75 and \$35.97 for tomatoes and almonds, respectively. The opportunity cost of time captures the value of time spent on behalf of the owner-operator learning to incorporate winter cover crops into his or her management system. This time may be spent making the decision to begin winter cover cropping (e.g. collecting relevant materials, reading, researching, attending workshops, talking with neighbors and fellow farmers) and implementing a new management plan (e.g. consulting with crop advisors and seed distributors, retrofitting equipment, disseminating instructions to crew members). The time was estimated to vary between 10 and 20 hours every year for the first 5 years of winter cover cropping. The value per hour is the same as the hourly wages used to estimate the direct costs.

Direct benefits were identical every year beginning in the fifth year of consecutive winter cover cropping [Creamer et al., 1996]. Yield benefits were estimated as a conservative 5% increase from the baseline yields for tomatoes and 2.5% for almonds to reflect agronomic benefits from improved soil health due to winter cover cropping based on grower interviews. Soil erosion control was estimated to be the foregone cost of new soil to replace soil lost due to runoff from fields, translated into U.S. dollars per lb. of potential soil lost per acre. On average, annual soil saved from erosion due to winter cover crops was estimated at 489.2 lbs. per acre, which was valued

based on the assumptions that top soil weighs 1,300 lbs. per cubic yard and is valued between \$25-50 per cubic meter [Malik et al., 2000, Nearing et al., 2017, Pratt et al., 2014, Robinson et al., 2014]. Fertilizer and herbicide cost savings were estimated to vary between 5 and 30% to capture the benefits of nutrient cycling and weed control, respectively. Fertilizer costs savings per acre were based on the prices per acre: \$396 for tomatoes, \$228.19 in the fifth year of almonds and \$290.12 during full production after the sixth year for almonds. Cost savings for herbicide were \$20 and \$60.56 per acre for tomatoes and almonds, respectively. The benefit of mycorrhizal fungi colonization was estimated to be the foregone cost of added soil amendments, estimated to be 2-8 tons of compost per acre, valued at \$14.58-72.91 per ton, every five years [Gravuer, 2016, Rahmani et al., 2004].

One variable differed between the models to address the different possible benefits for annual and perennial cropping systems. For annual tomato production, winter cover crops can improve soil structure and reduce tillage requirements to break up the soil surface and prepare the ground for transplanting in the spring. This benefit was estimated to be the savings associated with one less pass of machinery in winter cover cropped systems, valued using the same labor rate as in the direct costs. For perennial almond production, winter cover crops can provide an attractive pollination habitat for bees. Growers pay for beehives to pollinate almond trees every spring, and beekeepers may offer discounts to an orchard with cover crops that offer a more diverse foraging opportunity to the hive. These beehive discounts were estimated to be between 5-30% reduced costs that range from \$94.16 in the third year to \$470.81 after the sixth year based on prices from the Cost and Return study.

Indirect benefits were calculated similarly for both production systems. The benefit of increased soil organic matter captures the soil health improvements that winter cover crops provide. The monetary value per acre was based on the lowest and highest soil organic matter contributions from oil seed radish (\$21.72) and crimson clover (\$46.54), respectively [Pratt et al., 2014]. Winter cover crops can also reduce surface water runoff, and subsequent pollution [Wyland et al., 1996]. The range of prices for surface water discharge permits for the 2017-2018 fee schedule for California Code of Regulations TITLE 23. Division 3. Chapter 9. Waste Discharge Reports and Requirements was used as a proxy for savings from reduced surface water runoff because just 10% of ground



cover can correspond to a 30% improvement in erosion control [**Sarrantonio and Gallandt, 2003, California Code of Regulations,** ]. The lowest value was \$0.87 per acre and the highest value was \$4.76 per acre.

The benefit of soil-carbon storage describes how winter cover crops can mitigate climate change by sequestering atmospheric carbon. The monetary value was estimated based on the carbon sequestration potential of winter cover crops in California's Central Valley from the COMET Planner tool, which uses the DayCent crop model [**Swan et al.,** ]. The model estimates 0.3 or 0.15 tons of carbon is sequestered per acre-foot of seeded cover crops and residual vegetation, respectively. These estimates were valued by multiplying them by a range of \$14.54-75.10 per ton of CO<sub>2</sub>, estimates for the social cost of carbon from California's carbon market [**Auffhammer, 2018**].

TABLE A.3. List of raw values used to calculate costs and benefits associated with winter cover cropping in two specialty crop systems in California's Central Valley.

Budget components	Raw data used in calculations (low value per acre)	Raw data used in calculations (high value per acre)	Description	Sources
Processing tomatoes costs				
Seed	\$0.40	\$0.75	price per lb of seed	1
	60	120	lb cover crop seed	1
Planting (labor)	30	60	minutes of labor	1, 3
	\$19.21	\$19.21	hourly wage	2
Termination (labor)	60	120	minutes of labor	1, 3
	\$19.21	\$19.21	hourly wage	2
Harvest complications with cash crops	5	30	% of yield loss every 5 years	1
	\$55.50	\$85.50	return per ton tomatoes harvested	2
	43	73	tons per acre harvested	2

Depreciation of machinery	5	30	% of annual capital recovery costs depreciated	1
	\$75.00	\$75.00	annual capital recovery costs for equipment	2
Opportunity cost of time spent learning to grow cover crops	10	20	hours of learning	1
	\$19.21	\$19.21	hourly wage	2
Processing tomatoes benefits				
Increased yield	5	5	% increase	4
	\$55.50	\$85.50	return per ton tomatoes harvested	2
	43	73	tons per acre harvested	2
Soil erosion control	489.2	489.2	lbs topsoil lost without cover	3,5,6
	\$25.00	\$50.00	price of cubic yard topsoil	7
Nutrient cycling	5	30	% of fertilizer savings	1
	\$396.00	\$396.00	price of fertilizer	2

Weed control	5	30	% of herbicide savings	1
	\$20.00	\$20.00	price of herbicide	2
Mycorrhizal fungi colonization	2	8	tons of compost avoided	8
	\$14.58	\$72.91	price per ton of compost	9
Reduced tillage operations	\$15	\$25	price per pass	1
Increased soil organic matter	\$21.72	\$46.54	value of soil health improvements	1,3
Reduced surface water runoff	10	30	% of ground cover	10,11
	\$0.87	\$4.76	surface water discharge permits	12
Soil carbon storage	0.3	0.3	tons of sequestered carbon	13
	\$14.54	\$75.10	price per ton of carbon	14
Almond costs				
Seed	\$1.00	\$2.15	price per lb of seed	1
	20	40	lb cover crop seed	1

Planting (labor)	30	60	minutes of labor	1,2
	\$20.51	\$20.51	hourly wage	15
Termination (labor)	60	120	minutes of labor	1,3
	\$20.51	\$20.51	hourly wage	15
	2	4	mowing passes	1
	\$15	\$25	price per pass	1
Harvest complica- tions with cash crops	2.5	15	% of yield loss ev- ery 5 years	1,3
	\$2.62	\$2.62	return per lb al- monds harvested	15
	182	618	lbs almonds per acre harvested at year 3,15	
	364	1236	lbs almonds per acre harvested at year 4,15	
	727	2473	lbs almonds per acre harvested at year 5,15	
	1000	3400	lbs almonds per acre harvested at maturity	15

Depreciation of machinery	5	30	% of annual capital recovery costs depreciated	1
	\$35.97	\$35.97	annual capital recovery costs for equipment	15
Opportunity cost of time spent learning to grow cover crops	10	20	hours of learning	1
	\$20.51	\$20.51	hourly wage	15
Almond benefits				
Increased yield	2.5	2.5	% increase	4
	\$2.62	\$2.62	return per lb almonds harvested	15
	182	618	lbs almonds per acre harvested at year 3	15
	364	1236	lbs almonds per acre harvested at year 4	15
	727	2473	lbs almonds per acre harvested at year 5	15

	1000	3400	lbs almonds per acre harvested at maturity	15
Soil erosion control	489.2	489.2	lbs topsoil lost without cover	3,5,6
	\$25.00	\$50.00	price of cubic meter topsoil	7
Nutrient cycling	5	30	% of fertilizer savings	2
	\$228.19	\$228.19	price of fertilizer at year 5	15
	\$290.12	\$290.12	price of fertilizer at maturity	15
Weed control	5	30	% of herbicide savings	2
	\$20.00	\$20.00	price of herbicide	15
Mycorrhizal fungi colonization	3	8	tons of compost avoided	8
	\$14.58	\$72.91	price per ton of compost	9
Discounted beehives	5	30	% of beehive savings	1
	\$94.16	\$94.16	price of beehives at year 3	15
	\$188.32	\$188.32	price of beehives at year 4	15
	\$376.65	\$376.65	price of beehives at year 5	15

	\$470.81	\$470.81	price of beehives at maturity	15
Increased soil organic matter	\$21.72	\$46.54	value of soil health improvements	1,3
Reduced surface water runoff	10	30	% of ground cover	10
	\$0.87	\$4.76	surface water discharge permits	12
Soil carbon storage	0.3	0.3	tons of sequestered carbon years 1 to 3	13
	0.15	0.15	tons of sequestered carbon after year 4	13
	\$14.54	\$75.10	price per ton of carbon	14



TABLE A.4. List of sources for raw values used in the winter cover crop cost benefit analysis.

Monetary values based on	
Source	Publication
1	Conversations with farmers, extension specialists, and seed company representatives
2	Turini, et al. (2018)
3	Pratt, Tyner, Muth, Kladivko (2014)
4	Creamer, Bennett, Stinner, Cardina (1996)
5	Malik, Green, Brown, Mays (2000)
6	Nearing, Xie, Liu, Ye (2017)
7	Robinson et al. (2014)
8	Rahmani, Hodges, Kiker (2004)
9	Gravuer (2016)
10	Sarrantonio Gallandt (2003)
11	Wyland, et al. (1996)
12	Section 2200.6. Annual Agricultural and Irrigated Lands Fee Schedule (2017-2018)
13	COMET Planner tool by Swan et al. (n.d.)
14	Auffhammer (2018)
15	Duncan et al. (2016)

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